THE ELECTROWEAK SECTOR, EW SYM. BREAKING,
AND THE "THEORIST'S" STANDARD MODEL.

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Until now we've seen the "low energy" Standard Model
... particles that we've observed @ experiments.
THIS, however, does not elucidate the [ELEGANT]
theoretical structure of the SM.

Instead of continuing w/ the "low energy" theory,
I'm now going to focus on the FULL theory.

↳ It's a little more involved, but will
provide the insight that you need
to understand how the Higgs mechanism
works ? why we expect physics
Beyond the Standard Model

WE WILL STILL AVOID BEING TECHNICAL, BUT WE
WILL PRESENT THE full STRUCTURE of THE SM.

↳ you may have to adjust some
preconceptions you have about
particle physics !

# The Higgs "VEV"

WHAT IS $(h ----\!\!\!\rightarrow \times)$ ?

THIS TERMINATES A HIGGS LINE!

REPRESENTS THE HIGGS <u>VACUUM EXPECTATION VALUE</u> (VEV)

TO UNDERSTAND WHAT THIS MEANS, WE HAVE TO UNDERSTAND THE FRAMEWORK OF <u>QUANTUM FIELD THEORY</u>

           ↑      ↑

              eg. ELECTRIC FIELD

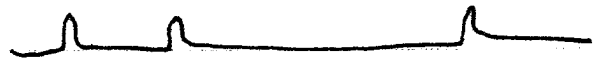DISCRETE EXCITATIONS (PARTICLES)

[WHY QFT? THIS IS THE MARRIAGE OF QUANTUM MECHANICS & RELATIVITY — the <u>FIELDS</u> ARE THE REQUIRED OBJECTS IN ORDER TO MAINTAIN SPACETIME SYMMETRIES! ]

<u>FIELD</u>: function defined over all of spacetime which tells us the probability of finding a 'particle' there. (ROUGHLY)
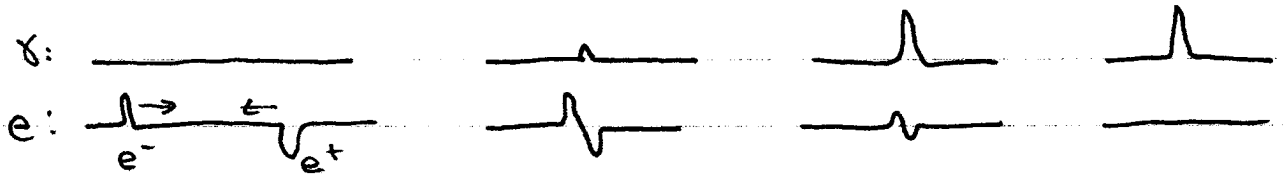
eg. PARTICLES :        •     •          •

FIELD LOOKS SOMETHING LIKE

q: ALL $e^-$ ARE <u>EXACTLY</u> THE SAME. WHY? eg. WHY NO SMALL ERROR IN ELECTRIC CHARGE? BECAUSE ALL ELECTRONS ARE EXCITATIONS OF <u>ONE</u> OBJECT: THE $e^-$ QUANTUM FIELD.

FIELDS ARE LIKE MATTRESSES.

INTERACTIONS BETWEEN FIELDS: (heuristic only!)

$\gamma$: ———————    ———∧———    ——∧——    ——∧——

$e$: ——↑→——←↓——    ——⋀⋁——    ——⋁——    ————
      $e^-$      $e^+$

for: ⟋⟍⟋

WHY IS THIS PICTURE USEFUL?

① MANIFESTLY SPACETIME (LORENTZ) INVARIANT MATHEMATICAL FORMULATION.

② QM DEALS W/ SINGLE PARTICLES THAT ARE CONSERVED. QFT GIVES A WAY TO USE $E = MC^2$ TO CREATE/ANNIHILATE PARTICLES.

FOR MOST PARTICLES, THE DEFAULT VALUE FOR THE QUANTUM FIELD IS OFF (ZERO). IN THE PERFECT VACUUM (ZERO ENERGY), THERE'S NO PROBABILITY TO FIND AN ELECTRON THAT WASN'T ALREADY THERE.

↳ note: actual space is not a perfect vacuum!

# BUT SOME EXCEPTIONS

IN THE PRESENCE OF A MACROSCOPIC CHARGED OBJECT, THE ELECTRIC FIELD HAS A <u>SOURCE</u>, re $\exists$ A <u>CLASSICAL</u> ELECTROMAGNETIC POTENTIAL.

↳ IN QFT, THIS IS INTERPRETED AS A BACKGROUND PROBABILITY TO FIND PHOTONS ⟺ EM FIELD.

↓

INDEED, PHOTONS ARE EXCITATIONS OF THE <u>QUANTUM</u> ELECTROMAGNETIC FIELD!

eg.: CHARGED CAT :



far away          looks like

eg: $\mu \to e$ CONVERSION IS NOT ALLOWED IN VACUUM, BUT IN A HEAVY MATERIAL (eg Ti) IT CAN INTERACT W/ THE BG W BOSON FIELD:



coming from the protons & neutrons
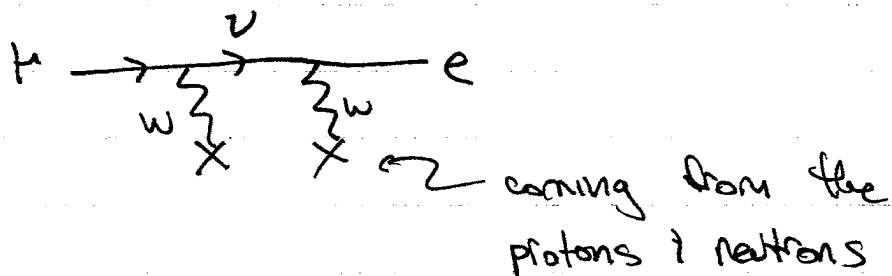
# "Advanced" Standard Model

### CAVEAT

USUALLY THESE ARE TOPICS THAT ONLY GET MENTIONED IN 2ND SEMESTER OF GRAD QUANTUM FIELD THEORY

... BUT OUR FEYNMAN DIAGRAM APPROACH GIVES US A WAY TO UNDERSTAND THEM WITHOUT RESORTING TO TEDIOUS MATH

... ALSO, THIS WILL GIVE THE <u>REAL</u> PICTURE of THE STANDARD MODEL ? WHY WE EXPECT IT TO BREAK DOWN.

WON'T BE TECHNICALLY DIFFICULT, BUT THE IDEAS ARE VERY DIFFERENT FROM WHAT YOU'RE USED TO.

### ROAD MAP

- MEANING OF MASS IN PARTICLE PHYSICS
  ↓
  RELATION TO SPIN ? HELICITY

SPIN $\frac{1}{2}$: FERMIONS

- SM IS "CHIRAL"
- MEANING OF ANTIPARTICLE
- RELATION TO HIGGS
- CHIRAL MATTER CONTENT OF THE SM

SPIN-1: GAUGE BOSONS

- POLARIZATION OF MASSIVE ? MASSLESS VECTORS
- GOLDSTONE BOSONS (the HIGGS)
- GAUGE REDUNDANCY

ELECTROWEAK SYMMETRY BREAKING
→ the Higgs ? its problems

THINGS GET A LITTLE MORE INVOLVED HERE... BUT THIS IS
AN HONEST (not watered-down) VERSION OF THE SM!

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# What is [THE SIGNIFICANCE OF] Mass?

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MASSLESS: TRAVELS @ THE SPEED OF LIGHT

YOU CAN NEVER BOOST INTO A FRAME (ie choose a reference frame) WHERE THE PARTICLE IS AT REST.

MASSIVE: YOU CAN ALWAYS CHOOSE A FRAME WHERE THE PARTICLE IS AT REST.

FACT: YOU CAN NEVER EXCEED THE SPEED OF LIGHT.
  ⌊ what I mean by 'fact': built in assumption in the framework of relativity — has been checked many times & many ways

FACT: PARTICLES CARRY INTRINSIC (QUANTUM MECHANICAL) ANGULAR MOMENTUM — SPIN. (just a property of each particle)

for us: don't have to worry about meaning of frac. spin.

FERMIONS: SPIN $\frac{1}{2}$   (or maybe also $\frac{3}{2}$)
BOSONS: SPIN 0 ⟶ Higgs
        SPIN 1 ⟶ gauge bosons
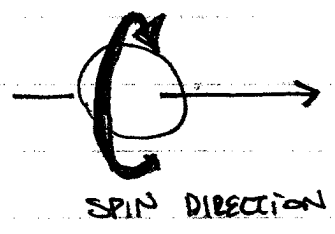        SPIN 2 ⟶ graviton

Remark: you can also have higher 'spin' mesons & baryons, but this is really coming from orbital angular momentum of the constituent quarks & gluons.

# Mass ⇒ SPIN

SUPPOSE YOU HAVE A "LEFT HANDED" FERMION, CALL IT $e$

SPIN $-\frac{1}{2}$  (convention)



SPIN DIRECTION

DIRECTION OF MOTION, $\hat{p}$
say in the $+z$ direction

($\vec{j}$ is PARALLEL TO $\vec{p}$)

∠ angular momentum vector

IF THIS FERMION ("ELECTRON") IS MASSLESS
THEN IT TRAVELS @ THE SPEED OF LIGHT
AND IS ALWAYS LH, no matter what reference
frame you're in.

ON THE OTHER HAND: IF THE ELECTRON HAS MASS
THEN IT IS ALWAYS POSSIBLE TO BOOST
INTO A FRAME WHERE IT ~~SPIN~~ IS MOVING
IN THE $-z$ DIRECTION & HENCE IS RIGHT-HANDED.



$v_e$

$v_{ROCKET} > v_e$

$\tilde{v}_e < 0$
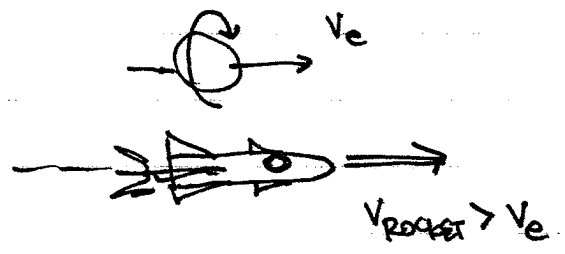
$\tilde{v}_{ROCKET} = 0$

EARTH FRAME
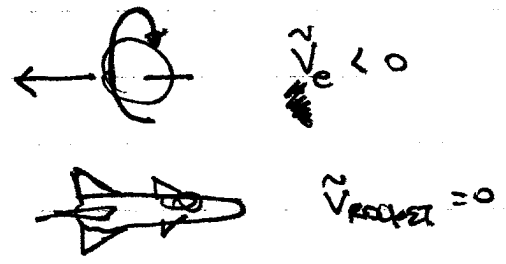
ROCKET FRAME

So for MASSIVE PARTICLES, THE ANGULAR MOMENTUM w/rt the direction of Motion is NOT a well defined quantity.

↳ it depends on the reference frame (because the "direction of motion" depends on the frame)

FOR MASSLESS particles, the direction of Motion does not change so this angular momentum is well defined always.

THIS HAS A FANCY NAME:

## Helicity : spin angular momentum along the direction of motion.

SO: MASS (zero or nonzero) tells us whether helicity is an intrinsic property of a particle.

[REMARK: MASS IS A CONTINUOUS VARIABLE! A "SMALL" MASS MEANS HELICITY IS ALMOST AN INTRINSIC PROPERTY]

↳ HW: what does "small" mean here? (hint: there is no such thing as a "small" dimensionful number!!)

<u>Remark</u> : there is another word that often shows up here:

chirality : the quantum mechanical sense in which a spin ½ particle is left or right handed.

↳ FOR MASSLESS PARTICLES : equivalent to helicity
BUT FOR MASSIVE PARTICLES : <u>still well defined!</u>

<u>RECALL</u> : A PARTICLE HAS A WAVEFUNCTION $\psi$
→ COMPLEX # WHOSE MAGNITUDE GIVES
THE PROBABILITY of OBSERVING THE PARTICLE

SPIN-½ MEANS : $\text{Rotate}_{360°}(\psi) = -\psi$
rotate particle by 360°, don't get the same wavefunction, but <u>MINUS</u> the original

IN GENERAL : $$\boxed{\text{Rotate}_\theta\, \psi = e^{\pm i\theta/2}\, \psi}$$



RIGHT CHIRAL

LEFT CHIRAL
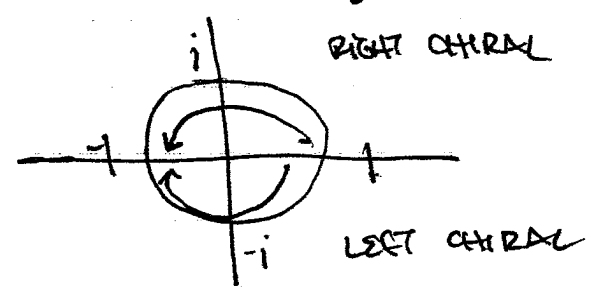
<u>Homework</u>: Understand the difference between helicity & chirality.

[ YOU HAVE UNTIL YOUR 2ND YR of GRAD SCHOOL...]

<u>so far</u>: Who cares?

ok, so a given massless fermion is LH (say, a $\nu$), and because [suppose] $m_\nu = 0$, it is always LH.

that means that somewhere there can also be a RH $\nu$ that has the exact same properties except it spins in the opposite direction: RH, and will always stay RH because $m_\nu = 0$... RIGHT ???

¡Wrong!

take a moment to let that settle — this is the most unintuitive thing I could have told you!

"the Standard Model is a <u>chiral</u> theory"

"it does <u>not</u> respect PARITY"

meaning: if we reversed left & right, then the universe would be noticeably different.

↑

same w/ biology: ON <u>EARTH</u>, ALL AMINO ACIDS ARE LEFT HANDED.
(they say left "<u>chiral</u>", but in our parlance they mean left helicity.)

IN MORE CONCRETE TERMS:

<u>FALSE</u>: ∃ EQUAL NUMBER of RH & LH MASSLESS $\nu$s
RH STAYS RH, LH STAYS LH IN ANY FRAME.

<u>TRUE</u>: (in the limit $m_\nu = 0$) ALL NEUTRINOS ARE LH!!

<u>RECALL</u>: WHY DO e ALL HAVE <u>EXACTLY</u> THE SAME CHARGE? THEY'RE ALL WIGGLES IN THE SAME QUANTUM FIELD. SAME STORY FOR $\nu$ HELICITY: THE QUANTUM FIELD IS LEFT HANDED — <u>ONLY</u> PRODUCES LH NEUTRINOS.

this is related to another observation:
the W-boson <u>only</u> talks to LH fermions!

the W is really weird.
BUT ACTUALLY, THE Z ALSO TALKS DIFFERENTLY
TO LH & RH FERMIONS.

this brings us to the point:

Left handed & Right handed
fermions are totally different
particles!

CAVEATS :

① this holds in even # of spacetime dimensions

eg in 5 dimensions your spacetime symmetry is
bigger & forces LH ⟷ RH

in 6 dimensions spacetime sym is even bigger
& provides a new def of LH & RH
to avoid the 5D restriction, — etc.

② Majorana particles
   ⤷ see lecture on Neutrinos by Josh.

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   & provides a new def of LH & RH
   to avoid the 5D restriction, ... etc.

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# Handedness & Antimatter

this all ties in with what we mean by <u>antiparticle</u>.

We 'know' intuitively that an antiparticle is somehow the "opposite" of the particle — but often this intuition fails unless we have a rigorous definition motivated by the framework of <u>QFT</u>

eg: MASS IS GRAV. CHARGE
... ∃ ANTI-MASS?

<u>PREDICTS</u> antiparticles
why? required for
spacetime (LORENTZ) sym.

So it shouldn't surprise you if I defined "antiparticle" w/rt SPACETIME SYMMETRIES:

ANTIPARTICLE = C P (PARTICLE)

CHARGE CONJUGATION    PARITY   $(L \longleftrightarrow R)$
                                        HELICITY

$(+ \rightarrow -)$

the <u>antipartner</u> of a given particle has opposite spin!

So: WHILE NEUTRINOS ARE ALL (almost) LH <u>ANTI NEUTRINOS</u> ARE THUS ALL RH!

   however, because neutrinos have no electric charge, hard to tell them apart.

HOMEWORK: GIVEN THAT THE W BOSON ONLY COUPLES TO LH $e^-$ & LH $\nu$

    (RH $e^+$ & RH $\nu^*$)

DESIGN AN EXPERIMENT TO CONFIRM CHIRAL NATURE OF SM.

IF NEUTRINOS ARE <u>MAJORANA</u>, THEN THEY ARE THEIR OWN ANTIPARTICLES! (see Josh's talk)

<u>HOMEWORK</u>: is CP (matter—antimatter) SYMMETRY A "GOOD" SYMMETRY of NATURE?

    → for more on this, see Monika's talk on FLAVOR PHYSICS.

[a good question: what does <u>flavor</u> have to do with CP?]

why should (ANTI) = C.P ?
↓ makes sense
↳ why PARITY?

CONSISTENT QUANTUM THY REQUIRES CPT SYMMETRY
↳ TIME REVERSAL
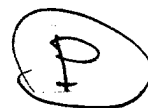
SO IF CPT IS A GOOD SYMMETRY,
THEN CP = T.
↳

time reversal:
electron moving forward
in time & space becomes
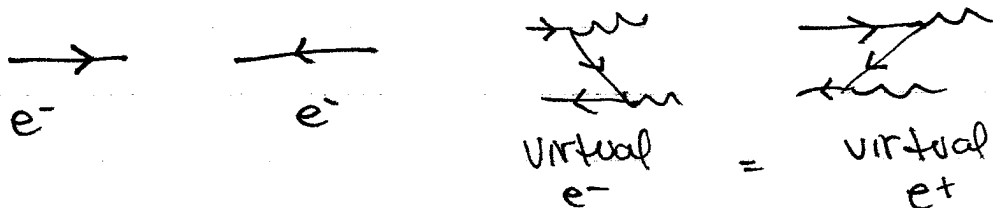electron moving backward
in time & space.

current switches
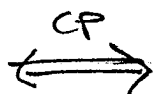direction, same
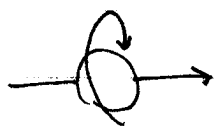as charge → minus charge

ⓒ

momentum
switches sign
→ spin (helicity)
flips sign too

ⓟ

SO: $e^-$ MOVING FWD IN TIME IS LIKE $e^+$ MOVING BACKWARD.
THIS IS EVEN IMPLIED BY FEYNMAN DIAGRAM ARROWS!

$\longrightarrow$           $\longleftarrow$
$e^-$                $e^-$

virtual
$e^-$

=

virtual
$e^+$

MINI RECAP : ASSUME MASSLESS "electron"



ELECTRON : $e_L$ , $q = -$, $h = LH$

    just a name!

"LEFT CHIRAL ELECTRON"

MIGHT AS WELL CALL IT "LARRY"
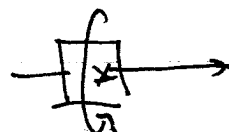
just happens to also have LH helicity

ANTI-ELECTRON : $(e_L)^*$    $q = +$

"ANTI - LARRY"      $h = RH$

opposite charge and helicity

- - - - - - - - - - - - - - - - - - - - - - - - - - -

NOW A COMPLETELY UNRELATED PARTICLE
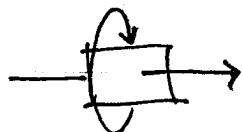


ANTIPOSITRON : $e_R$    $q = -$

again, just a name    $h = RH$

might as well call it "ROB"

has RH helicity!

~~the 'R' denotes chirality~~

~~of the positron~~

POSITRON : $(e_R)^*$    $q = +$

"anti-Rob"      $h = LH$

REMARK: this is important. in SUSY (see Jack's talk) YOU DOUBLE the spectrum. there is a superpartner for $e_L$ and $e_R$, not just one superpartner for $e$!

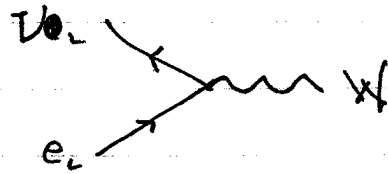<u>Caution</u>: even though $e_L$ & $e_R$ look like they're related, they are totally different!!

<u>FOR EXAMPLE</u>: the W boson <u>only</u> talks to left handed particles!

ie $e_L$, LARRY



<u>QUICK HW</u>: ASSUMING THAT SPIN IS ADDITIVE, CONVINCE YOURSELF THAT THIS VERTEX CONSERVES ANGULAR MOMENTUM. (W IS SPIN-1) [hint: use your hands if you are confused]

~~IF THE W WAS WERE SO~~

IF WE REPLACE THE W WITH A SPIN-0 PARTICLE, WOULD THIS VERTEX BE ALLOWED? WHAT DO YOU CONCLUDE ABOUT THE WAY A SPIN-0 PARTICLE (eg Higgs) MUST COUPLE TO CHIRAL FERMIONS?

$e_L$ & $e_R$ are two independent massless particles.

<u>PUNCHLINE</u>: $e_L$ & $e_R$ COMBINE TO FORM A <u>MASSIVE</u> PARTICLE $e$ WHICH IS THE USUAL "electron" THAT WE KNOW & LOVE.

How does this happen? the Higgs!

THE PREVIOUS 'HOMEWORK' SHOULD HAVE CONVINCED
YOU of THE FOLLOWING FACT:

Angular momentum conservation implies
that spin-1 bosons couple to
fermions of the same chirality,
while spin-0 bosons couple to
fermions of opposite chirality:
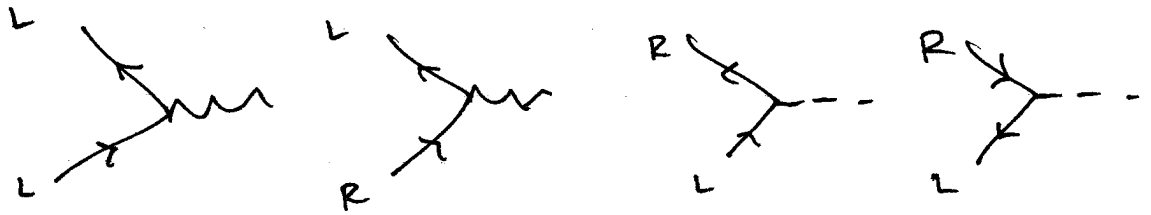


- the Higgs is a special spin-0 particle;
it has a VACUUM EXPECTATION VALUE (vev)
? can do this:



this is precisely a mass term!
MASS: MIXES LEFT & RIGHT.
this is <u>exactly</u> what we said on p.54!

Relating our two pictures of mass

Higgs vev: an omnipresent background that fermions can "bounce off" to change chirality.

↳ $e_L$ & $e_R$ MIX. THIS IS ANALOGOUS TO THE WAY NEUTRINO FLAVORS MIX!! [inherently quantum mechanical]

$e_L \longrightarrow\!\!\times\!\!\longrightarrow e_R$    IS ALSO A PROBABILITY AMPLITUDE

aka proportional to the elec mass } YOU HAVEN'T LEARNED HOW TO CALCULATE THESE AMPLITUDES YET, BUT IT SHOULD BE BELIEVABLE THAT IT IS PROPORTIONAL TO THE HIGGS VEV. BUT THE VEV IS DIMENSIONFUL, $[V] = 1$. (take as a fact)

PROBABILITY IS DIMENSIONLESS.

⇒ NEED ANOTHER DIMENSION-1 SCALE (mass) TO CONSTRUCT A PROBABILITY. THE ONLY OTHER SCALE IN THE SYSTEM IS THE ENERGY, SO THE PROB. AMPLITUDE $\sim V/E$ OR $M_e/E$

⇒ PROBABILITY $\sim (V/E)^2$ OR $M_e^2/E^2$

BUT E IS FRAME-DEPENDENT! SO @ LARGE BOOST, E IS LARGE AND THE MASS IS small (relative to E) ⇒ PROB TO CHANGE CHIRALITY IS TINY, AS EXPECTED for A VERY RELATIVISTIC PARTICLE TRAVELING NEAR c!

# Gauge bosons

Z, W are massive gauge bosons.
WHERE DO THEIR MASSES COME FROM?
→ also the Higgs! BUT A DIFFERENT MECHANISM.

diagram:



mass term.
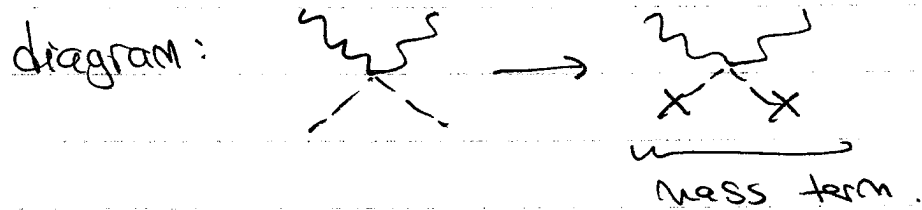
BUT SOMETHING SUBTLE IS HAPPENING.

MASSLESS SPIN-1: eg. $\gamma$, ELECTROMAGNETIC FIELD

COMES IN TWO POLARIZATIONS: LH, RH POLARIZATION

(spin +1, spin -1)

OR:
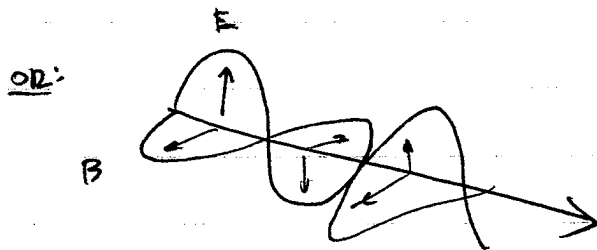


two "degrees of freedom"
for $\gamma$ polarization.

WHY? IMAGINE $\gamma$ HAD SOME RADIUS:



← LH OR RH POLARIZ
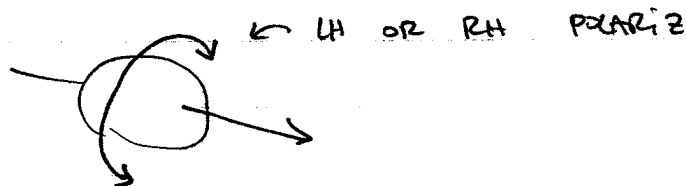
WHY NO FORWARD - BACKWARD POLZ?

REMARK: We call spin-1 particles <u>VECTOR</u> particles because their polarization is described by a vector. Special relativity relates space & time, so the vector is not a ~~3~~ 3-component vector, but a <u>four</u>-component "4-vector" $A_\mu$. $\mu = 0, 1, 2, 3$

CLASSICAL ANALOG: ELECTROMAGNETIC FIELD IS DESCRIBED BY AN ELECTRIC POTENTIAL $\phi$ AND A 3-VECTOR POTENTIAL $\vec{A}$

RELATIVITY TELLS US THAT THESE SHOULD BE COMBINED INTO A 4-VECTOR: $A_\mu = (\phi, A_1, A_2, A_3)$ this 4-vector correctly describes classical electromagnetism. ↳ see PHYS 3327 this fall!

~~Now something interesting: a ⊥~~

the photon is the quantum excitation of $A_\mu$ different photon polarizations correspond to different $A_\mu$ excitations.

<u>Remark II</u> : but a 4-vector has ④ components. we just argued that massless spin-1 particles have 2 polarizations, while massive particles have 3. what's with the missing polarizations?

we saw that the difference between massive & massless is the <u>longitudinal</u> polarization. (SPECIAL RELATIVITY)

what about the fourth polarization?

<u>ANSWER</u> : (very deep) there is no $4^{th}$ polarization. the mathematical object which describes spin-1 simply has too many degrees of freedom (components). in order to account for this, we define an <u>equivalency class</u> between field configurations — ie we identify an entire degree of freedom to be unphysical & redundant.

NOT REALLY A 'SYMMETRY' AT ALL!

↳ this is called a <u>gauge symmetry</u> and <u>this</u> is the origin of fundamental forces !!

[the formalism is deeply rooted in differential geometry & is very elegant]

↳ IF YOU'RE INTERESTED: hep-th/0611201

Gauge bosons & the Higgs

In order for the Z & W to become massive, they need to acquire a third (longitudinal) component.

Where do these components come from? It turns out that they originally belonged to the <u>Higgs</u>!

The full Standard Model Higgs:

$$\begin{pmatrix} H^+ \\ h^0 + ia = H^0 \end{pmatrix} \xleftarrow[\text{TO}]{\text{COMPARE}} \begin{pmatrix} \nu \\ e \end{pmatrix} \text{ & } \begin{pmatrix} u \\ d \end{pmatrix}$$

$H^+$ and $H^-$

usual "Higgs"

neutral extra guy
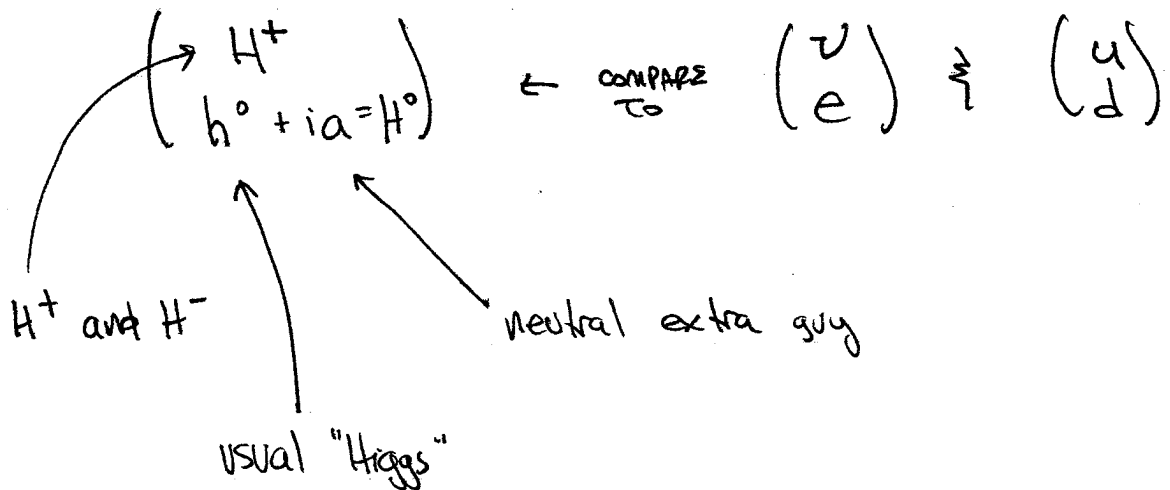
the $H^+, H^-$, and $a$ ARE CALLED <u>Goldstone bosons</u>

↳ in the SM they give their lives to become the longitudinal polarization of the $W^{\pm}$ & Z.

"massive gauge boson <u>EATS</u> a Goldstone boson"

In diagrams:



Higgs vev
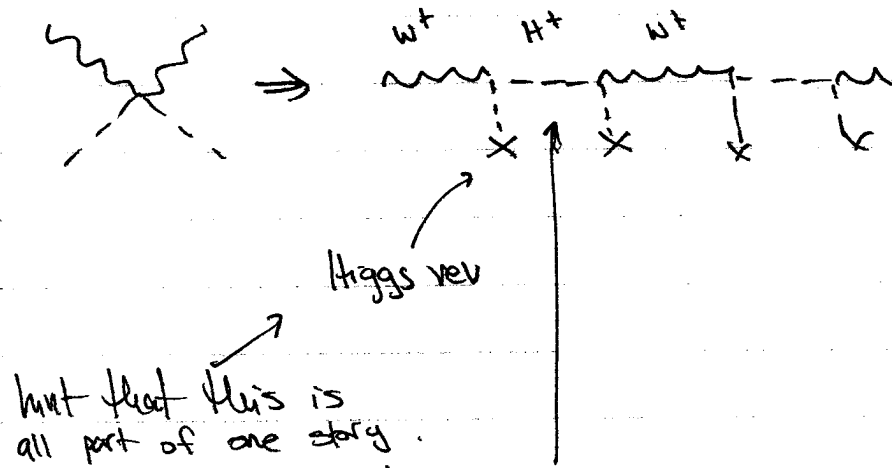
hint that this is
all part of one story.

$W^+$
〰 is <u>mixing</u> into a $- - -$ $H^-$

(just like neutrino mixing, &
just like $e_L - e_R$ mixing)

~~Simple story for circle with relativity~~

~~massive spin 1: can boost into rest frame~~

~~where you can~~

NOTE How spin-$\frac{1}{2}$ fermions are different from spin-1
gauge bosons! The origin of these differences
come from spacetime symmetry & the structure
of quantum mechanics.

So the point: Gauge bosons (force particles) get mass by <u>eating</u> parts of the Higgs called <u>Goldstone bosons</u>.

<u>Fermions</u> (matter particles) get mass by <u>bouncing</u> off of the Higgs <u>vacuum</u> <u>expectation</u> value (vev).

<u>So the full SM particle content</u> :

|  | before "EWSB" | after "EWSB" |
|---|---|---|

MATTER :  $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$

$u_R$

$d_R$     $\Big\}$ massive $u$ / massive $d$

$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

$e_R$     $\Big\}$ massive $e$ / massless $\nu$

FORCE :  $\gamma$     $\longmapsto \gamma$

$Z$     massive $Z$ (eats $a$)

$W^{\pm}$     massive $W^{\pm}$ (eats $H^{\pm}$)

$g$     $\longmapsto g$

HIGGS :  $H \Big\{ \begin{array}{l} h \\ a \\ H^{\pm} \end{array}$     $\longmapsto h$

$\Big\}$ eaten.
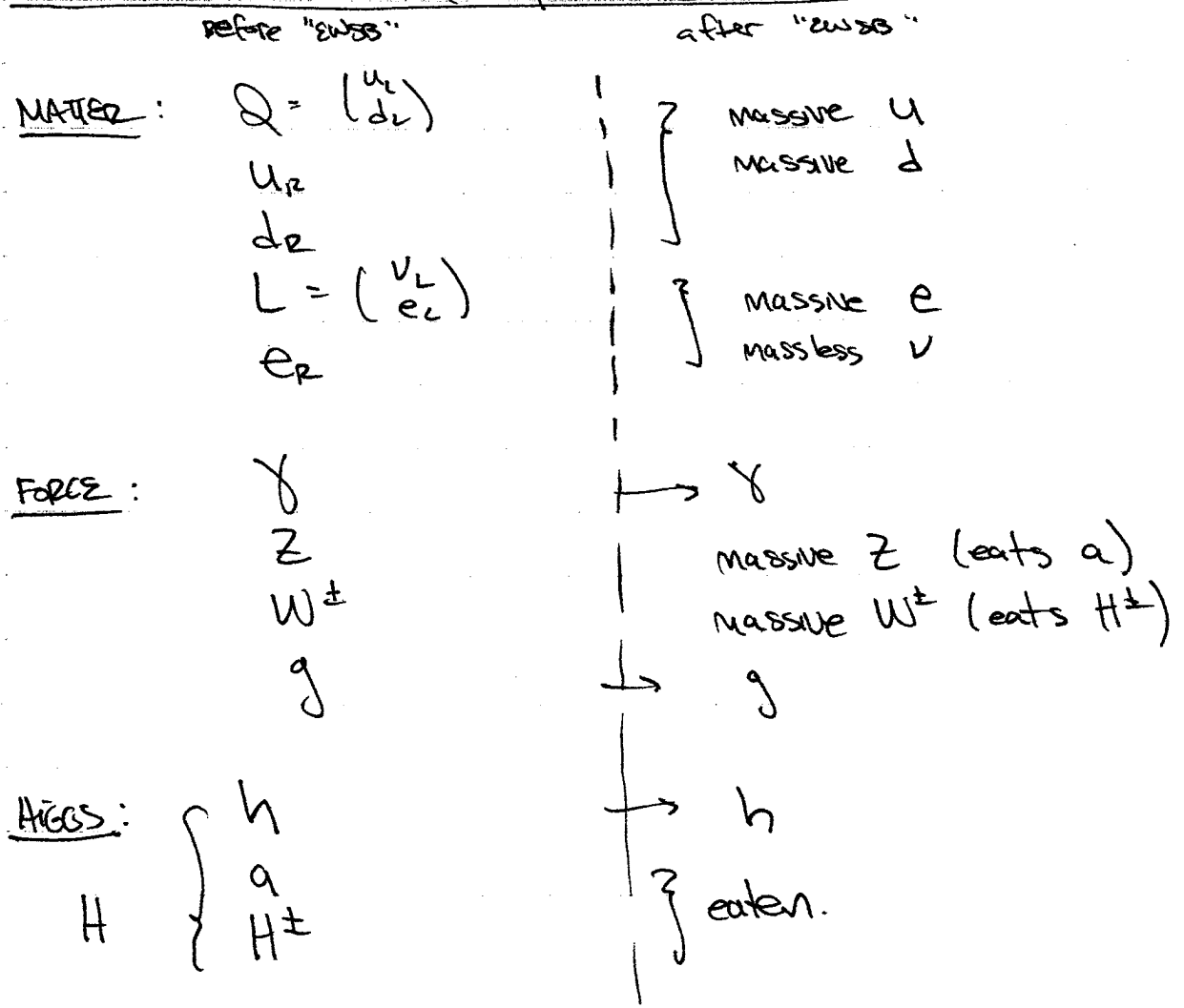
Electroweak symmetry & its breaking

this whole story of vevs, Goldstones, & mass is related to the <u>unification</u> of the <u>electromagnetic</u> & <u>weak forces</u>.

$\gamma$                 $W, Z$

<u>"antediluvian" SM forces</u> — no such thing as EM!

$B$          hypercharge       (like photon)
$W^{1,2,3}$   electroweak force    three gauge bosons
$g$          strong

ALL SM PARTICLES TALK TO B
<u>ONLY</u> 4 PARTICLES TALK TO W!
        $\uparrow$
        $Q, L$      (& also H, but nevermind)

eg.    but no
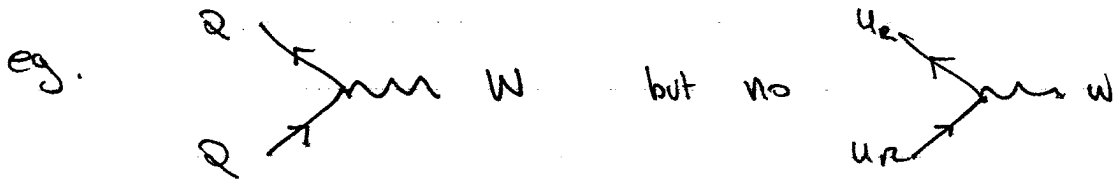
but then: the potential energy for the Higgs is such that it acquires a <u>VeV</u>. this vev is charged under hypercharge & electroweak → these "symmetries" are broken.

instead:   $\left.\begin{array}{c} B \\ W^3 \end{array}\right\}$   combine into $\gamma, Z$

$\left.\begin{array}{c} W^1 \\ W^2 \end{array}\right\}$   combine into $W^{\pm}$

<u>electroweak + hypercharge</u> → electromagnetic

4 massless force particles            1 massless force particle
                                      & 3 massive guys.
                                              ↑
                                      from eating Goldstones.

this is called <u>ELECTROWEAK SYMMETRY BREAKING</u>
  · Higgs gets vev → fermion mass
  · Higgs partially eaten → gauge boson mass
  · one gauge boson left massless → leftover ~~gauge~~ symmetry

"Higgs mechanism"

# EWSB summary

start w/ massless chiral fermions: $Q, u_R, d_R, L, e_R$
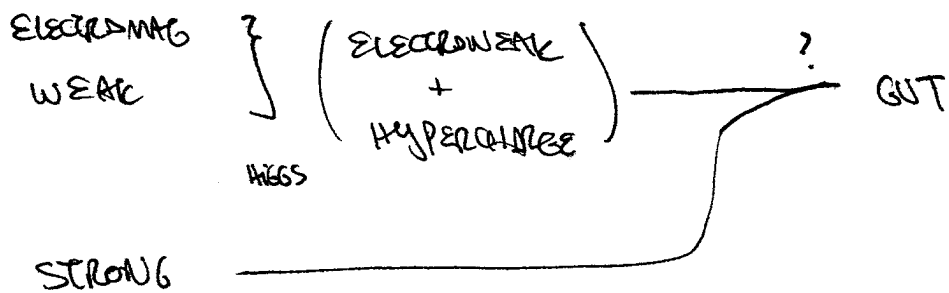and electroweak + hypercharge : $B, W^{1,2,3}$

Higgs sector: vacuum expectation value     ①
   → offers $H^{\pm}, a$   for sacrifice     ②

① →   $Q, u_R, d_R \longrightarrow u, d$
        $L, e_R \longrightarrow \nu, e$

② →   $B + W^3 + a \rightarrow \gamma, Z$
     $\underline{\underline{W^1 + W^2 + H^{\pm}}} \rightarrow W^{\pm}$

       ↑ explains why $W^{\pm}$ only talks to
      LH particles! [ the story of the
      $H^{\pm}$ here is a little more complicated ]
      also explains why we wrote $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$.

IT IS HOPED THAT the ELECTROWEAK + HYPERCHARGE FORCE
CAN ALSO BE UNIFIED W/ THE STRONG forces:

ELECTROMAG ⎫
WEAK    ⎬ $\left(\begin{array}{c} \text{ELECTROWEAK} \\ + \\ \text{HYPERCHARGE} \end{array}\right)$ ——— ? —— GUT
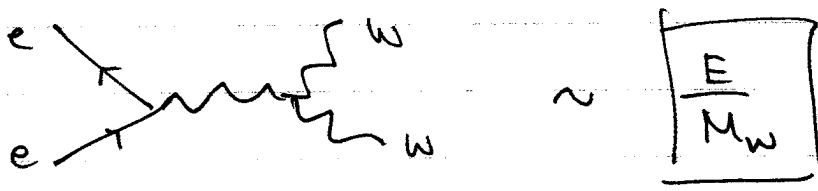   HIGGS

STRONG ————————————

See Jack's talk on SUSY.

Why we need the Higgs
→ EWSB sounds complicated, why bother?

Massive gauge bosons don't behave well @ high
energies. EWSB via the Higgs solves these
problems. ~~@ high energi~~

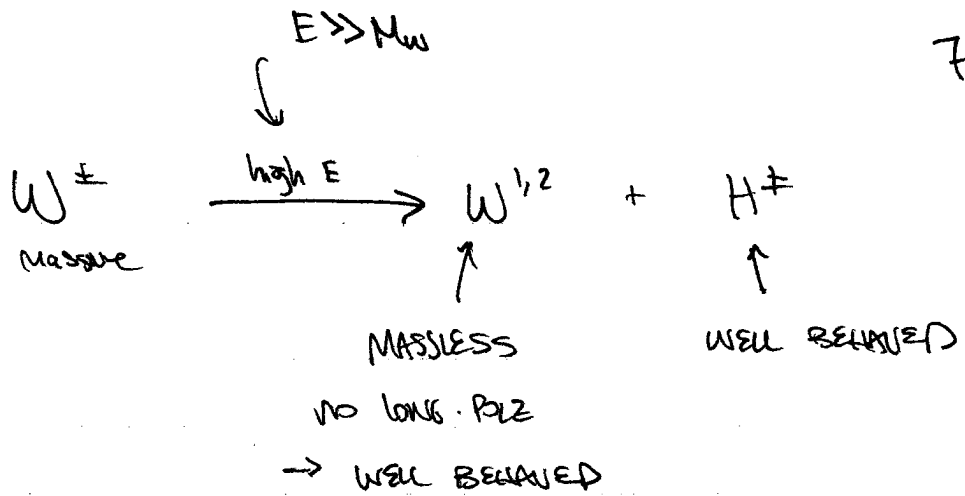eg: $e^+e^- \to W_L^+ W_L^-$ ← longitudinal



$\sim \boxed{\dfrac{E}{M_W}}$

for large E, this is arbitrarily large!!

PERTURBATION THY BREAKS DOWN (Taylor exp. fails)
↳ thy is strongly coupled! ⏐

BUT: if there was EWSB & the W got its
mass from eating a goldstone, then
@ high energies we recover this behavior.

(eaten goldstone is liberated!)

$$E \gg M_W$$

Idea:

$$W^{\pm} \xrightarrow{\text{high } E} W^{1,2} + H^{\mp}$$

massive

$W^{1,2}$: MASSLESS

NO LONG. POLE

$\rightarrow$ WELL BEHAVED

$H^{\mp}$: WELL BEHAVED

HOW IS THE $E/M_W$ BEHAVIOR FIXED?
BY INTERFERENCE w/ OTHER DIAGRAMS!



EACH DIAGRAM HAS "BAD" $E/M_W$ BEHAVIOR.
BUT THE __SUM__ DOES NOT. THIS CANCELLATION
APPEARS MIRACULOUS, BUT IT IS __MANDATED__
BY THE STRUCTURE IMPOSED BY THE HIGGS
OBTAINING A VEV !!

# Problems of the SM

1. <u>NEUTRINO MASS</u> : almost a trivial extension
   ↳ but may hint at something more!
   eg "SEE-SAW" MECHANISM POINTS TO GUT SCALE
      & SUGGESTS A MORE COMPLICATED GUT theory
   → see Josh's talk.

2. <u>DARK MATTER</u> : not in SM! what is it?
   → see bibhushan's talk

3. <u>baryogenesis</u> : how did we get all this <sup>baryonic</sup> matter?
   → see Nic's talk on cosmology

4. <u>CP problem</u> : there's a nonperturbative (no feynman rule)
   effect which violates CP by a lot... but doesn't
   seem to exist in the SM. why?

5. <u>FLAVOR</u> : why 3 generations? why are their
                masses so different?
   → see Monika's talk on flavor.

⑥ <u>Hierarchy problem</u> : WHY IS THE HIGGS SO LIGHT?

# Hierarchy Problem

QUANTUM CORRECTIONS want to make the Higgs heavy.

quantum uncertainty ~ thermal uncertainty
IN FACT, THIS LENDS ITSELF TO A GOOD
ANALOGY: a snowball's chance in hell.

if you put a snowball in an oven
for a while, what is the probability
that it will stay cold?

→ tiny. thermal bath wants to
make the snowball warmer.
[BUT THEORETICALLY POSSIBLE... HIGHLY IMPROBABLE
UNLESS YOU HAVE A REASON WHY THE SNOWBALL
DOESN'T GET WARMER!]
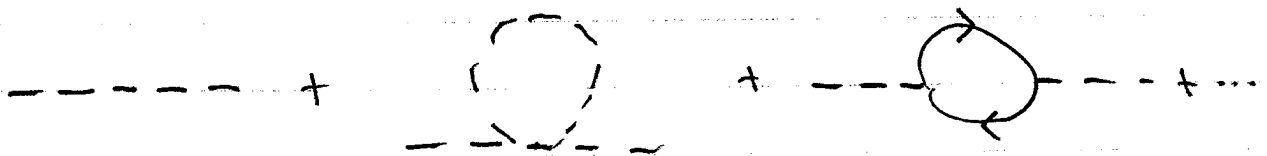
snowball ⟶ Higgs
temp. ⟶ mass  (both are energy!)

thermal ⟶ quantum  } we'll see
bath        corrections   what this
                          means

# Higgs mass in diagrams

Unlike spin-$\frac{1}{2}$ & spin-1, spin-0 has no "story" about massive vs. massless. This leads to the mass of spin-0 particles becoming a problem.

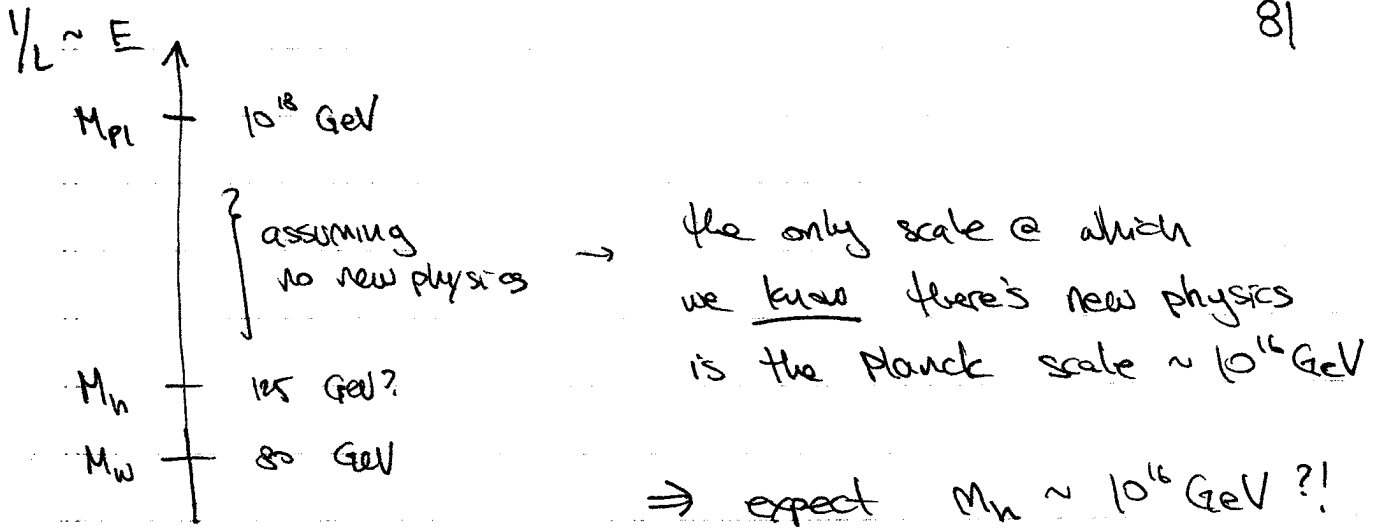RECALL: "MASS" CAN BE DRAWN AS A 2-point diagram.



LOOP DIAGRAMS: QUANTUM CORRECTIONS (VIRTUAL PARTICLE CONTRIBUTIONS)

RECALL THAT THESE LOOP DIAGRAMS HAVE UNCONSTRAINED ENERGY & MOMENTA, SO WE HAVE TO SUM OVER THEM. THIS IS AN INFINITE SUM & for THIS DIAGRAM, THE SUM DIVERGES !!

↳ HIGGS MASS WANTS TO BE ∞?
NO — DIVERGENCE MEANS OUR THEORY BREAKS DOWN. @ SOME LENGTH SCALE, SM is REPLACED BY SOMETHING ELSE.

$1/L \sim E$

$M_{Pl}$ ---- $10^{18}$ GeV

{ assuming
no new physics → the only scale @ which
we **know** there's new physics
is the Planck scale $\sim 10^{18}$ GeV

$M_h$ ---- 125 GeV?

$M_w$ ---- 80 GeV

$\Rightarrow$ expect $M_h \sim 10^{18}$ GeV ?!

→ the problem is that we **need** a light
Higgs to solve the problem of massive
gauge bosons (eg $e^+e^- \to w^+w^-$).

if Higgs is $10^{18}$ GeV, it's too heavy to
be produced at $E \sim M_w$ & cannot help.

But once we have a light Higgs, we have
to explain how it stays light when
it really wants to get heavy.

we say the Higgs mass must be "**fine-tuned**"

↳ a bit hard — feel free to ask me later!

EXERCISE: WHY NO fermion/gauge boson HIERARCHY PROBLEM?

LET'S ARGUE BASED ON <u>DIMENSIONAL ANALYSIS</u>.
ACCEPT THE FOLLOWING AS FACTS:

$$\xrightarrow{\quad k \quad} \quad \sim \quad \frac{1}{k}$$

$$\xrightarrow{\quad k \quad}\mathrm{\sim\!\sim\!\sim} \quad , \quad -\!-\xrightarrow{\quad k \quad}-\!- \quad \sim \quad \frac{1}{k^2}$$

FURTHER, EACH LOOP GOES LIKE $\int d^4 k$
↳ SUM OVER INDEP. ENERGY, $k_x$, $k_y$, $k_z$

So, for example:

$$-\!-\!-\bigcirc\!-\!-\!- \quad \sim \int d^4k \; \frac{1}{k}\cdot\frac{1}{k} \sim \int^{\infty} dk \; k \sim k^2 \Big|_{k\to\infty}$$

↑
POWER LAW DIVERGENT.

WHAT ABOUT <u>FERMIONS</u> & GAUGE BOSONS? SHOW ONLY log DIVERGENCE.

↑
hint: use chirality

note: $\overset{L+}{\underset{\quad}{\rule{1.2cm}{0.4pt}}}\!\times\!\overset{R+}{\rule{1.2cm}{0.4pt}} \quad \sim \quad M$

$$-\!-\zeta^-\!- \quad \sim \quad k$$

A sketch of solutions to the Hierarchy Prob:

1. ACCEPT FINE TUNING. (eg SPLIT-SUSY, ANTHROPIC ...)
   ↳ cop out answer! we will not consider this

2. COMPOSITENESS : eg. ∃ SPIN-0 MESONS. WHY NO
   MESON HIERARCHY PROBLEM? @ HIGH ENERGY, YOU STOP
   SEEING A SPIN-0 MESON & YOU SEE A PAIR OF
   SPIN-½ PARTICLES.   ie REPLACE $M_{pl} \to M_{composite}$.

SEE
YUHAN'S
TALK

      ↳ ALTERNATELY, YOU CAN TELL THIS STORY USING
        THE LANGUAGE OF EXTRA DIMENSIONS.
      → other games you can play to keep the mass
        light   if the Higgs is composite

3. CANCELLATION : the loop diagrams happen to
   cancel w/ each other.

         → Supersymmetry.
           see jack's talk

## PRELUDE TO SUSY

to tie together some ideas here & to give an idea of how "doubling the spectrum" (a la susy) can solve hierarchy problems. let's consider the question of the electron mass / self-energy in classical vs. quantum thy.

the electron has "rest energy" $M_e c^2$ but obtains a correction from the energy of the electric field it generates:

$$\Delta E_{coulomb} = \alpha / r_e \quad \leftarrow \text{"radius" of electron}$$

$$r_e \lesssim 10^{-17} cm \rightarrow \Delta E \cong 10 \, GeV$$

$$[\text{OBSERVED REST ENERGY}] = M_e c^2 + \Delta E$$
$$\overset{\text{unobserved}}{\phantom{M_e c^2}}$$

$$.5 \, MeV \quad = (-9.005 + 10) \, GeV$$
$$\underbrace{\phantom{-9.005}}$$
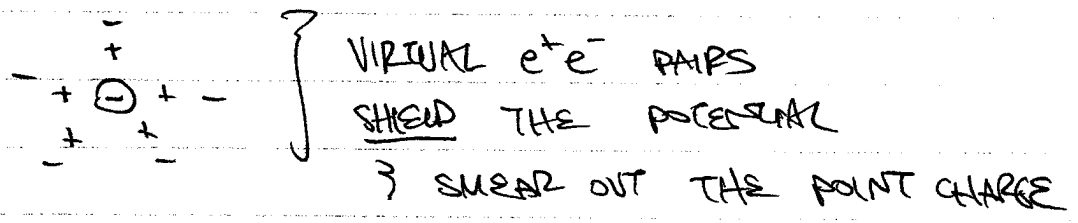$$\text{fine tuning}$$

THIS 0.1% TUNING SEEMS SILLY.

~~FACTS~~

To AVOID THIS TUNING, WOULD NEED THE COULOMB POTENTIAL TO "BREAK DOWN" @

$$\bar{r} = \frac{e^2}{\alpha M_e c^2} \sim \boxed{3 \times 10^{-13} \, cm}$$

INDEED, IT IS. THE COULOMB POTENTIAL IS
SINGULAR @ CLASSICAL LIMIT — BUT NOT IN
THE QUANTUM LIMIT.

VIRTUAL $e^+ e^-$ PAIRS
SHIELD THE POTENTIAL
& SMEAR OUT THE POINT CHARGE

THESE VIRTUAL PAIRS OBEY (roughly) $\Delta t \Delta E \sim \hbar$

$$\Rightarrow \quad \Delta t \sim \hbar / \Delta E = \hbar / (2 M_e c^2)$$

CHARACTERISTIC DISTANCE:

$$d \sim c \Delta t \sim \hbar c / (2 M_e c^2) = \boxed{200 \times 10^{-13} \text{ cm}}$$

cf $3 \times 10^{-13}$ cm

SO QUANTUM MECHANICS SAVES US
@ A LENGTH SCALE 100 TIMES LARGER THAN NEEDED.

↑

wiggle room.

QUANTUM CORR. TO

ANALOG: SUPERPARTNERS SHIELD ∧ HIGGS MASS. !