Polariz Picture

So far

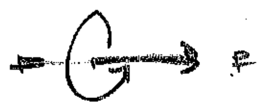
$SU(2) \times U(1)_Y \to U(1)_{em}$

QudLe $\to \boxed{u, d, e}$, ν_L

u, d, e: massive Dirac fermion

ν_L: Weyl (chiral)

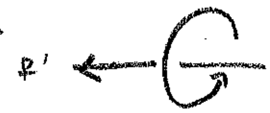
Fermions:



RH helicity
in massless
limit = RH chirality

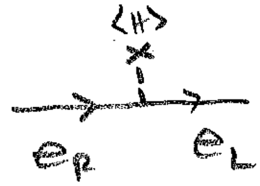
e_R

Boost (kinematic) →



LH helicity

Higgs (dynamic) →

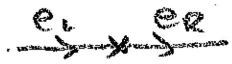


converts into LH chirality

These are the same phenomenon in two pictures!

Higgs vev → mass to (most) fermions

$e_L e_R^\dagger$ + h.c. term in Lagrangian



Quantum mixing

can boost into frame where LH helicity → RH

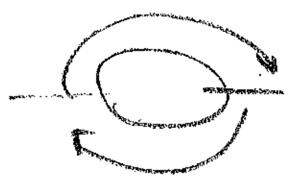
Kinematics.

Spin-1: LH more subtle

SPIN - 1 :

MASSLESS : 2 polarizations (spins)
LH & RH , but w/ integer spin

literally LH & RH polariz of LIGHT.

MASSIVE :  longitudinal POLARIZATION

only if massive...
cartoon : "top" of particle is moving forward faster than middle

→ so if massless, middle moves @ velocity = c

→ "top" is SUPERLUMINAL !

EACH POLARIZ IS A "DEGREE of FREEDOM"
"whole particle's worth"
eg. massive Dirac fermion = 2 $\not{c}$ dof ✓ IMPLIED 2 MASSL. FERMIONS

MASSLESS SPIN-1 / GAUGE BOSON : 2 dof
MASSIVE SPIN-1 / ——"—— : 3 dof
↑ where did 3rd come from ?

FROM the HIGGS!

SIMPLE U(1) CASE:

$$H = \underbrace{a + ib}_{} = \underbrace{r e^{i\theta}}_{}$$

2 real dof (2 real particles)

ASSUME $\langle H \rangle = v/\sqrt{2}$

btw: can see where $\sqrt{2}$ comes from:

$H = \frac{1}{\sqrt{2}}(a+ib) =$

So, write: $H = \langle H \rangle + h = \langle H \rangle + a + ib$

NOW GAUGE the U(1) REPHASING SYM, ASSUME $q = 1$

$$D_\mu H = (\partial_\mu + igq B)(\langle H \rangle + h)$$

$$= igqB\frac{v}{\sqrt{2}} + \partial h + \underbrace{igqBh}$$

$\partial_\mu a + i\partial_\mu b$

when I square this gives terms w/ >2 fields

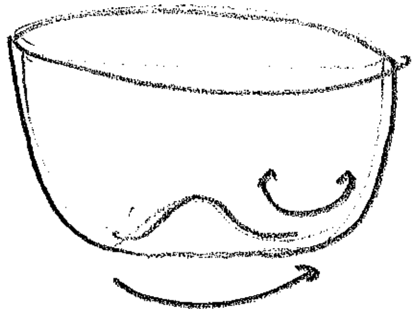
$$|D_\mu H|^2 = (\text{real})^2 + (\text{im})^2 + (>2 \text{ fields})$$

$$= (\partial_\mu a)^2 + \underbrace{(gqB_\mu + \partial_\mu b)^2}$$

the B_μ mixes w/ DERIVATIVE of $b = \text{Im}\, h$.

Dynamically: B has "EATEN" the b

(GOLDSTONE BOSON)



$V[H]$ is parabolic $\sim m^2 h^2$
in this dir

$V[H]$ is flat in this dir: no <u>MASS</u> term.

the component of the HIGGS that
has no mass term = GOLDSTONE BOSON

<u>HIGGS MECHANISM</u>: GAUGE BOSONS
ACQUIRE MASS BY MIXING ("EATING")
the GOLDSTONE BOSONS of the
HIGGS FIELD.

$\hookrightarrow$ INTIMATELY TIED TO
SPONTANEOUS SYM BREAKING
(VACUUM of thy BREAKS sym,
even if thy is symmetric!)

IN EWSB: $\underbrace{gW^3 - g'B}_{\sim Z}$, $\underbrace{W^+, W^-}_{\mathbb{C}\text{ field}}$ pick up mass

can confirm: $Q_{EM} = T^3 + Y = \frac{1}{2} + \frac{1}{2}$
EATEN BY W^+

$$H = \begin{pmatrix} \varphi^+ \\ h + i\varphi^0 \end{pmatrix}$$

EATEN BY Z

h = "the" HIGGS
125 GeV

} the only indep particle
in the HIGGS.

FLAVOR

the QudLe's have a GLOBAL symmetry index.

↑ no force particle

(no local transform)

$$\underbrace{Q^{i_Q}\ u^{i_u}\ d^{i_d}\ L^{i_L}\ e^{i_e}}$$

$$U(3)^5 = [SU(3)\times U(1)]^5$$

there are actually 3 copies of each

$$\underbrace{\begin{matrix} u & c & t \\ d & s & b \\ e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{matrix}}$$

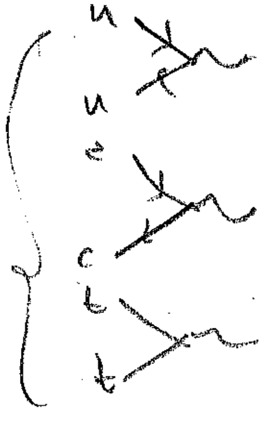
"generations" or "FLAVOR"

usually these indices mind their own business

e.g. $\underbrace{Q^\dagger_{i_Q}\bar{\sigma}^\mu D_\mu Q^{i_Q}}$

kinetic term + GAUGE interactions

never get mixed up



EXCEPT: YUKAWAS

$$y_u \, Q^{\dagger}_{i_Q} \, H^{\dagger} \varepsilon \, u_R^{\,i_u}$$

different indices!

$(y_u)^{i_Q}{}_{i_u}$ must have indices
→ promote to a MATRIX

but y_u does not transform.
it's not a field.

no picture that $y_u = \langle Y \rangle$ is called SPURION.

so $U(3)^5$ sym. is BROKEN
↳ EXPLICITLY by YUKAWAS

theory breaks sym.
[well, one portion of theory
... and if y's are small,
we can use APPROXIMATE sym.

MASS TERMS:

$$\underbrace{\left(\frac{v}{\sqrt{2}} y_u\right)^{i_Q}{}_{i_u}}_{M_u{}^{i_Q}{}_{i_u}} (u_L^{\dagger})_{i_Q} \, u_R^{\,i_u}$$

MASS MATRIX

MASS MATRIX ~ MATRIX of SPRING CONSTANTS IN NORMAL MODE PROBLEM

$\longrightarrow$ DIAGONALIZE FLAVORS.

flavor symmetric limit: u, c, t are IDENTICAL.

BUT: YUKAWA MATRIX $y_u \sim m_u$ DISCRIMINATES!

↳ by how much?

FACT: a matrix is diagonalized by a biunitary transf.

DIAGONAL

$$y_u = U_R^\dagger \, \hat{y}_u \, U_u$$

diff unitary matrices.

$$Q^\dagger \tfrac{v}{\sqrt{2}} y_u \, u_R = \underbrace{Q^\dagger U_R^\dagger}_{Q'} \tfrac{v}{\sqrt{2}} \hat{y}_u \underbrace{U_u u_R}_{u_R'}$$

new def in flavor space

eg $u_R' = \underbrace{(u_R', c_R', t_R')}$

each is some lin combo. of u_R, c_R, t_R in old basis nb: the kinetic terms don't change

$$u_R^\dagger \bar\sigma D u_R \to u_R'^\dagger \underbrace{U_R \bar\sigma D U_R^\dagger}\, u_R'$$

$u_R = U_u^\dagger u_R'$

$$= U_R U_R^\dagger \bar\sigma D$$
$$= \bar\sigma D$$

So nothing changes except we have diagonalized the mass terms (YUKAWAS)

so: this was the "RIGHT" basis.

& can now move to this basis in flavor space & drop primes.

so... $y_u, y_d, y_e \to$ diagonal matrices

& eigenvalues $= \frac{m}{v/\sqrt{2}}$ for each flavor.

(btw: can use U(1) rephasing to make all masses real)

<u>EXCEPT</u>: this works for LEPTONS.

$L_e = \begin{pmatrix} 0 \\ e_L \end{pmatrix} \to \underbrace{L_e^\dagger U_L^\dagger \frac{v}{\sqrt{2}} y_e U_e}_{\text{DIAG.}} e_R$

BUT QUARKS.

different matrices

$Q_u = \begin{pmatrix} u_L \\ 0 \end{pmatrix} \to Q_u^\dagger \boxed{U_Q^\dagger} \frac{v}{\sqrt{2}} y_u U_u u_R$

$Q_d = \begin{pmatrix} 0 \\ d_L \end{pmatrix} \to Q_d^\dagger \boxed{U_Q^\dagger} \frac{v}{\sqrt{2}} y_d U_d d_R$

<u>SAME</u> MATRIX!!

CANNOT simultaneously diagonalize the UP AND DOWN YUKAWAS!

(nb: APPRECIATE that this comes from the u_L & d_L living in same SU(2) doublet!

no prob for e_L, ν_L b/c no ν YUKAWA!)

WHAT TO DO?!

want to work in mass eigenbasis (commutes w/ Hamiltonian)

LET'S do GROSS VIOLENCE to the sym:

$$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \to \begin{pmatrix} U_\uparrow u_L \\ U_\downarrow d_L \end{pmatrix} \qquad (*)$$

(I DON'T HAVE this symm... doing this will cost me...)

then:

$$Q_u^\dagger \boxed{U_\uparrow^\dagger \tfrac{v}{\sqrt{2}} y_u U_u} u_R$$

$$Q_d^\dagger \boxed{U_\downarrow^\dagger \tfrac{v}{\sqrt{2}} y_d U_d} u_R$$

can diagonalize each

LET'S CALL $u_L' = U_u u_L$

by SU(2) sym $d_L' = U_u d_L$

$$Q^\dagger \bar{\sigma} D Q \supset (u_L^\dagger \ d_L^\dagger)\, ig\tfrac{1}{2}\begin{pmatrix}1 & \\ & -1\end{pmatrix} W^3 \begin{pmatrix}u_L\\ d_L\end{pmatrix}$$

$$(u_L^\dagger \ d_L^\dagger)\, ig\tfrac{1}{\sqrt{2}}\begin{pmatrix} & W^+ \\ W^- & \end{pmatrix} \begin{pmatrix}u_L\\ d_L\end{pmatrix}$$

the W^3 line is unchanged under (2.1)

BUT $W^\pm$ line:

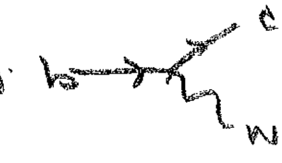
$$(u_L^\dagger U_\uparrow^\dagger \ \ d_L^\dagger U_\downarrow^\dagger)\begin{pmatrix} & W^+ \\ W^- & \end{pmatrix}\begin{pmatrix}U_\uparrow u_L\\ U_\downarrow d_L\end{pmatrix}$$

$$= (u_L'^\dagger \ \ d_L'^\dagger \underbrace{U_\uparrow U_\downarrow^\dagger}_{V_{CKM}^\dagger})\begin{pmatrix} & W^+ \\ W^- & \end{pmatrix}\begin{pmatrix}u_L' \\ \underbrace{U_\downarrow U_\uparrow^\dagger}_{V_{CKM}} d_L'\end{pmatrix}$$

$$= u_L'^\dagger W^+ V_{CKM}\, d_L' + d_L'^\dagger V_{CKM}^\dagger W^- u_L'$$

$W^\pm$ INTERACTIONS w/ QUARK DOUBLET CHANGES FLAVOR ACCORDING TO V_{CKM}!

$\sim g(V_{CKM})^j{}_i$

e.g.


$\sim g(V_{CKM})^3{}_2$