today: RILEY – HW3 #2

HW3 #3,4 ______

______

so can use $\langle H \rangle$ to break up doublets

LAST TIME: EW symmetry is BROKEN

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$$

ELETROMAGNETIC SYMMETRY SURVIVES!

$$\text{photon: } A \sim \underbrace{Y + W^3}$$

I'm calling it A now

some linear comb. coeff. tbd

what is EM sym? it is a U(1) (overall rephasing)

"REPHASE IN THE T^3 (W^3) DIRECTION AND IN THE Y DIRECTION BY THE SAME AMOUNT"

What is the ELECTRIC CHARGE of A PARTICLE?

↳ if you do the two rephasings, (by $\theta_Y = \theta^3 \equiv \theta$) the electric charge q^{EM} is the coefficient of θ in the exp.

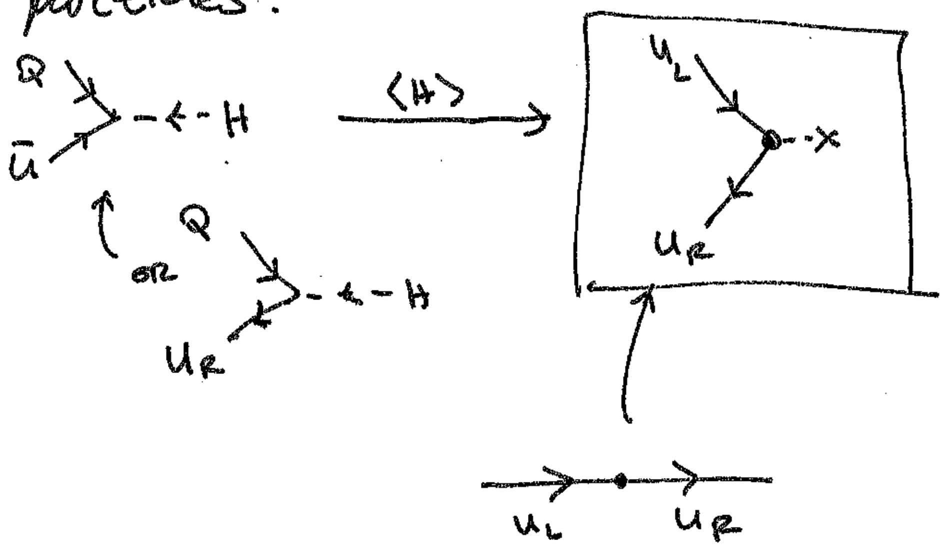
$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \to \begin{pmatrix} e^{i\theta\frac{1}{6}}\, e^{i\theta\frac{1}{2}}\, u_L \\ e^{i\theta/6}\, e^{i\theta(-\frac{1}{2})}\, d_L \end{pmatrix} = \begin{pmatrix} e^{i\theta\frac{2}{3}}\, u_L \\ e^{i\theta(-\frac{1}{3})}\, d_L \end{pmatrix}$$

ELECTRIC CHARGES!

ex: DO this FOR ALL PARTICLES

Meanwhile: Quark particles are being paired up by Yukawa terms w/ Higgs vev.

what does it mean to have a feynman rule that is just 2 particles?



PARTICLE MIXING

$\Leftrightarrow$ MASS TERM

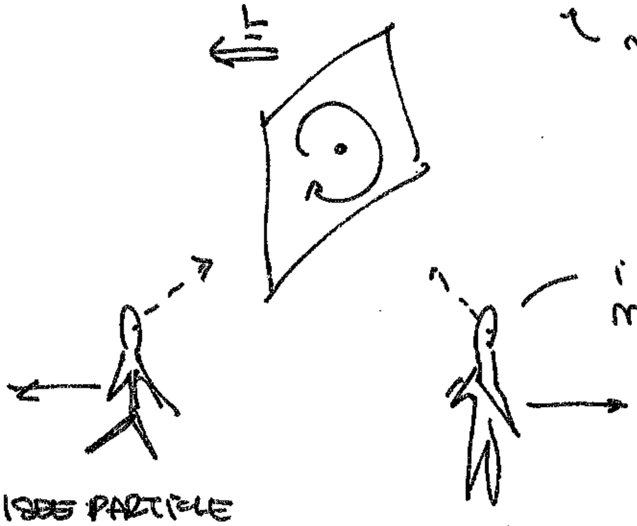
the following description is a little heuristic
(it's a little sloppy w/ helicity $\longleftrightarrow$ chirality)
$\longrightarrow$ but I want you to develop intuition

A MASSLESS PARTICLE W/ SPIN (ie w/ ANGULAR MOMENTUM)
travels @ speed of light $\leftarrow$ $p^2 = E^2 - \cancel{M^2}^{\,0}$

you cannot boost into its frame
... & certainly cannot boost "past it"

compare to particle @ "rest" w/ transv. polz.

← not possible for massless



I SEE THE PARTICLE MOVING TO THE LEFT

... LOOKS LIKE SPIN IS ALIGNED W/ MOTION

" RH "

I SEE PARTICLE MOVING RIGHT

... LOOKS LIKE SPIN IS ANTI-ALIGNED W/ MOTION

" LH "

[this may be a good "demo" in class]

So: having a mass $\longleftrightarrow$ can boost "past" rest frame s.t. you "reverse" the particle's 3-momentum (relative to you)

changes helicity (in YOUR frame)

$\Updownarrow$

same as chirality in massless limit

So: MASS → MIXING OF CHIRALITY

A PHYSICAL, MASSIVE PARTICLE:

MASS BASIS ("eigenstate of Hamiltonian") state is a <u>mixture</u> of chiral states.

(in a LAGRANGIAN ... but that's not obvious)

We found "mass terms"

$$m_d(d_L d_R^\dagger + d_L^\dagger d_R) + m_u(u_L u_R^\dagger + u_L^\dagger u_R)$$

$$m_e(e_L e_R^\dagger + e_L^\dagger e_R)$$

nb: from this you can see: "equal" mix of L & R

DOUBLET

SINGLET

different interactions (get "averaged" over)

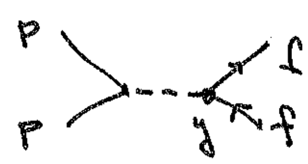
→ nb relativistic limits are different!

recall: $m_f \sim y_f \frac{v}{\sqrt{2}}$

f is <u>flavor</u> (type) of matter

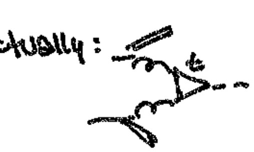
f = (u, d, e ... t, c, b, s, μ, τ, ...)

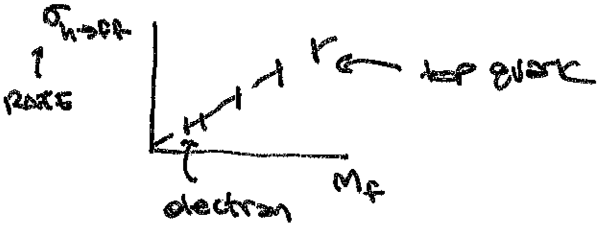
☆ SO WE CAN TEST: strength of higgs coupling vs mass of particles



← $\sigma \sim |\mathcal{M}|^2 \sim y^2$

actually:





GAUGE BOSONS

invariant: (not obvious) i'm deliberately hiding part of it.

$$\underbrace{\left[H^{+}_{i} \left(g W_{\mu}{}^{i}{}_{j} + g' q^{Y}_{H} Y_{\mu} \delta^{i}_{j} \right) \right]}_{[\ldots^{+}]_{j}} \underbrace{\left[\left(g W^{\mu j}{}_{k} + g' q^{Y}_{H} Y^{\mu} \delta^{j}_{k} \right) H^{k} \right]}_{[\ldots]^{j}}$$

int strengths $\quad \frac{1}{2} \quad \frac{1}{2}$

now insert $\langle H \rangle$

$$\left[\left(0 \;\; \frac{v}{\sqrt{2}} \right) \left(\frac{g}{2} \begin{pmatrix} W^3 & \sqrt{2} W^- \\ \sqrt{2} W^+ & -W^3 \end{pmatrix} + \frac{g'}{2} \begin{pmatrix} Y & \\ & Y \end{pmatrix} \right) \right] \left[\text{similar} \right]$$

$$\left(0 \;\; \frac{v}{\sqrt{2}} \right) \frac{1}{2} \begin{pmatrix} g W^3 + g' Y & g\sqrt{2} W^- \\ g\sqrt{2}\, W^+ & -gW^3 + g' Y \end{pmatrix}$$

$$= \frac{v}{2} \left(g W^+ \,,\; \frac{-gW^3 + g'Y}{\sqrt{2}} \right) \qquad \frac{v}{2} \begin{pmatrix} g W^- \\ \frac{-gW^3 + g'Y}{\sqrt{2}} \end{pmatrix}$$

$$[\ldots^{+}][\ldots] = \frac{v^2}{4} \left(g^2 W^+ W^- + \frac{1}{2} \left(-g W^3 + g' Y \right)^2 \right)$$

$$\equiv M_W^2 W^+ W^- + \frac{1}{2} M_Z^2 Z^2$$

b/c $Z^+ = Z$ (not imp.)

$$\boxed{M_W^2 = \frac{g^2 v^2}{4}}$$

$v^2 = (246 \text{ GeV})^2$
$g \longrightarrow$ from interactions.

normalize Z:

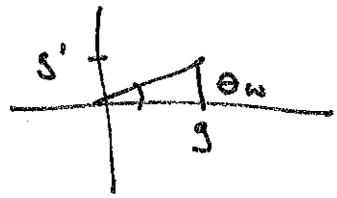
"Weinberg angle"

$$Z = \cos\theta_W W^3 - \sin\theta_W Y$$

$$A = \sin\theta_W W^3 + \cos\theta_W Y \quad \leftarrow \text{photon is ORTHOG COMB!}$$

from: $Z = \mathcal{N}(-gW^3 + g'Y)$

$\;\;\;\; \& \;\; \mathcal{N} = \dfrac{1}{\sqrt{g^2+g'^2}}$



or: $\boxed{\tan\theta_W = g'/g}$

$$\boxed{M_Z = \frac{v^2}{4}(g^2+g'^2)} \quad \leftarrow \text{from } \mathcal{N}: \; (-gW^3+g'Y) = \mathcal{N}^{-1} Z$$

again: we have a relation of Higgs vev
w/ interaction strengths
& mass of particles.

relates observables

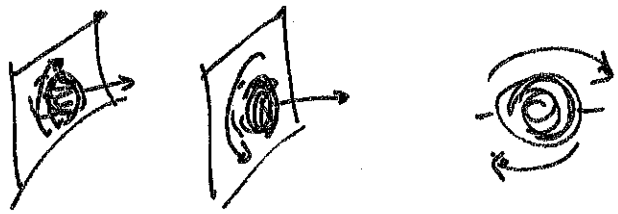
can make predictions

Degrees of freedom → "PARTICLE" states

MASSLESS SPIN-1 : 2 DOF

↳ general truth: massless particles w/ nonzero spin → 2 DOF (HELICITY)

MASSIVE SPIN-1 : 3 DOF !



LH RH "tumbling" (LONGITUDINAL POLZ)

familiar from EM waves

↳ eg EM waves in PLASMA

so when W^+, W^-, Z get MASS, they need to "pick up" a particle

↳ turns out: it's the 3 dof in H that we didn't use!

$$H = \begin{pmatrix} h^+(x) \\ \frac{v}{\sqrt{2}} + h(x) + i h^0(x) \end{pmatrix}$$

"GOLDSTONE" EATEN BY W^+

$W^+ \sim\sim - \overset{h^+}{-} \sim\sim W^+$

vev

the HIGGS

"GOLDSTONE" "EATEN" BY Z

$Z \sim\sim - \overset{h^0}{-} - \sim\sim Z$