TO DO: MIDTERM DOODLE POLL

So far:

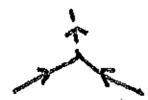
Model

1. Symmetries → Global, → Gauge
2. Fields (PARTICLES)
3. $\mathcal{L} = \underbrace{(\text{QUADRATIC})}_{\text{mass \& kinetic term.}} + (\text{INTERACTIONS})$ ← Vertices

FACTS

① $\mathcal{L}$ is REAL.

eg $y H^{\dagger} \cdot L \bar{E} + (h.c.)$ ← $y^* H L^{\dagger} E$


$\xrightarrow{\text{auto.}}$


SWAP ALL PARTICLES W/ ANTIPARTICLES

(charge-parity symmetry ... if $y^* = y$)

② $\mathcal{L}$ is made of $\underbrace{\text{couplings, invariant tensors,}}_{\text{what the "rule" is for the vertex}}$ $\underbrace{\text{fields}}_{\text{particles that go into vertex}}$

4-component $\bar{\psi} = \psi^{\dagger}\gamma^0$

③ $\mathcal{L}$ IS INVARIANT UNDER THE SYMMETRIES

④ THE QUADRATIC TERMS ARE STANDARD:

$(\partial\phi)^2 - m^2\phi^2$ for scalar ($\frac{1}{2}$ if $\mathbb{R}$)

$\psi^{\dagger}\gamma^0\gamma^{\mu}\partial_{\mu}\psi - m\psi^{\dagger}\gamma^0\psi$ for fermion

$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - m^2 A^2$ for gauge boson

$\partial_{[\mu}A_{\nu]} - g[A_{\mu}, A_{\nu}]$

not resp for this

BUT KNOW THE MASS TERMS

FACT: GAUGE INTERACTIONS come "for free"

HOW? PROMOTE $\partial_\mu \to D_\mu \equiv \underset{\uparrow \atop \delta^\Delta_\nabla}{\partial_\mu} - igA^a_\mu T^{a\,\Delta}{}_\nabla$

where Δ, ∇ are indices of object it's acting on w.r.t. GAUGED sym.

eg. $\underset{\uparrow \atop \text{for } L^a_{Y=-1/2}}{D_\mu} = \Big(\delta^a_b\,\partial_\mu - \underbrace{\underbrace{igW^A T^{Aa}{}_b}_{SU(2)} - \underbrace{\delta^a_b\, i g' Y B_\mu}_{U(1)_Y}}\Big)$

g's ARE COUPLINGS, typically small!

then:

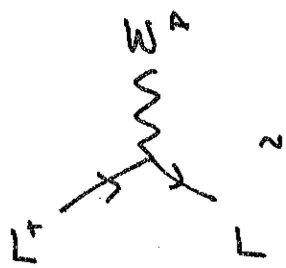
won't be careful w/ γ^0 →

USUAL KINETIC TERM

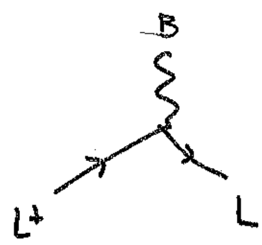
$$iL^\dagger_a \gamma^\mu \underbrace{(D_\mu L)^a}_{D_\mu{}^a{}_b L^b} = L^\dagger \gamma^\mu \partial_\mu L \longrightarrow L$$

$$- igW^A_\mu L^\dagger \gamma^\mu T^A L$$

$$- ig' q_L B_\mu L^\dagger \gamma^\mu \underset{\uparrow \atop \delta^a_b}{} L$$



$\sim ig\gamma^\mu T^A$



$\sim ig'\gamma^\mu \delta\, q_L$ ← CHARGE UNDER Y!

connects different components of SU(2) doublet

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

connects ν_e to ν_e, e_L to e_L

(doesn't "see" SU(2))

GAUGE BOSONS

$\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \sim (\partial A - gA^2)$ ← not caring about indices

$\sim (\partial A)^2$ ← 

$- g(\partial A) A^2$ ←  $\sim gP$ ← same momentum

$- g^2 A^4$ ←  $\sim g^2$ ← HIGHER ORDER!

this is why we didn't care about the 4-point int. too much.

eg: GLUONS:

color neutral

INDEX CARD:

QUARK DOUBLET:

$$Q^m = \begin{pmatrix} u_L^m \\ d_L^m \end{pmatrix} \qquad Y = 1/6 \qquad SU(3) \text{ TRIPLET } (m=1,2,3)$$

KINETIC TERM: $Q^\dagger i D_\mu \gamma^\mu Q$

$$D_\mu = \partial_\mu - igW_\mu^A T^A - ig' B - ig_c G^M T^M$$

HIGGS DOUBLET:

$$H = \begin{pmatrix} H^1 \\ H^2 \end{pmatrix} \qquad Y = 1/2 \qquad \text{KIN}: (\partial H)^2 \to |DH|^2$$

what interactions?

Higgs : $DH \sim \partial H - igW^A T^A H - ig' g_H B H$

$\Rightarrow |DH|^2 \sim |\partial H|^2$ (I)

$igW^A (\partial H)^\dagger T^A H$ + h.c. (II)

$ig' g_H B (\partial H)^\dagger H$ + h.c. (III)

$g_H g g' (W^A T^A H)^\dagger B H$ + h.c. (IV)

$g^2 |W^A T^A H|^2$ (V)

$g_H^2 (g')^2 |BH|^2$ (VI)

(I) 

(II) 

$\sim gPT^A$

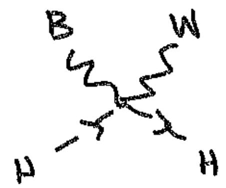
the h.c. swaps which momentum you pick up ...

RESULT IS $\sim g(P_1 - P_2)T^A$

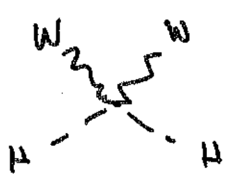
(III) 

$\sim g' g_H P$

nb: why no g_H in W vertex? it's hidden in T^A ... factors of 1/2

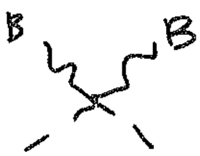
(IV) 

$\sim g g' g_H T^A$

(V) 

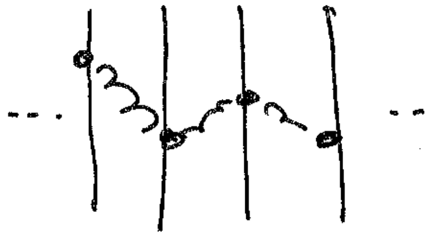
$\sim g^2 (T^A)^2$ ← ends up as $\sim \mathbb{1} \cdot \frac{1}{4}$

↑ from $(\frac{1}{2})\sigma^i$

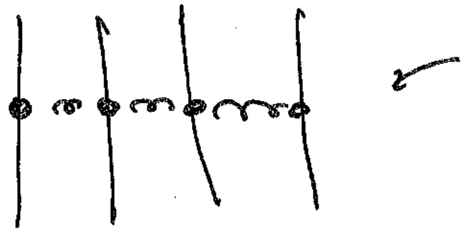
(VI) 

$\sim g_H^2 (g')^2$

SO FAR:

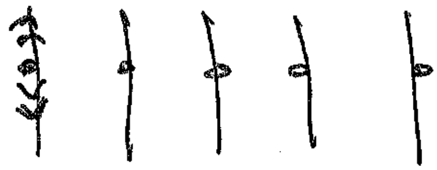


costs energy



"ground state"
(all oscillators the same in space-time)

A PARTICLE IS A QUANTUM WIGGLE THAT DISTURBS THIS



$a^\dagger_i$

$a^\dagger_{i+1}$

$a^\dagger_{i+2}$

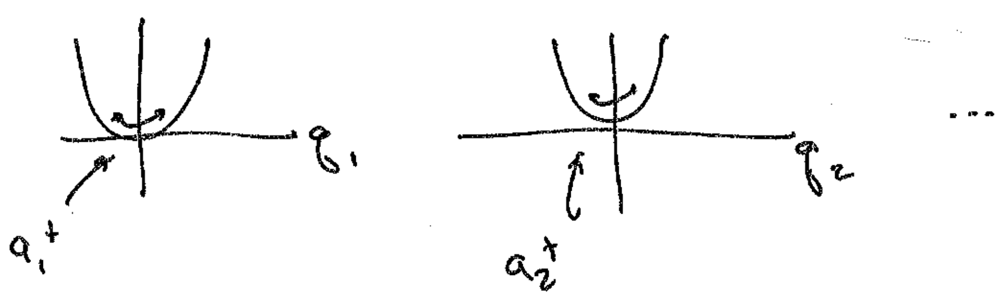
BUT WHAT SETS THE ZERO VALUE OF THE FIELD?

$L = T - V$

kinetic, POTENTIAL

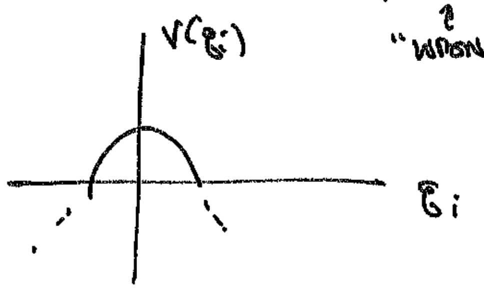
eg $\int d^4x \; \underbrace{-m^2 \phi(x)^2}_{V \sim m^2 \phi^2}$

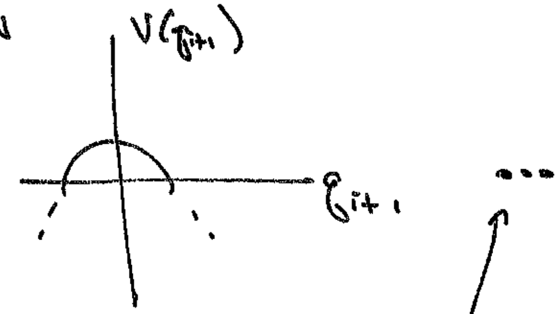
$$\int d^4x \, |\phi(x)|^2 = \phi_i^2 + \phi_{i+1}^2 + \phi_{i+2}^2$$



BUT WHAT IF... $\mathcal{L} = +m^2\phi^2$

"WRONG" SIGN





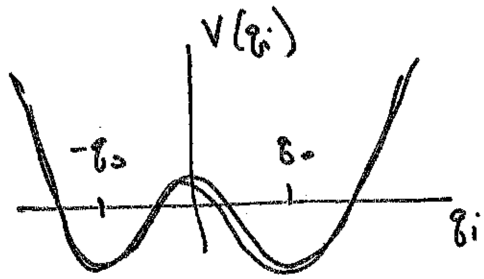
$q_i = 0$ is not vacuum.

ARE THEY ALL THE SAME?
YES → BY SPACETIME SYMMETRY!
?
doesn't always have to be the case

... no vacuum...
doesn't make sense

[nb: looks tachyonic]

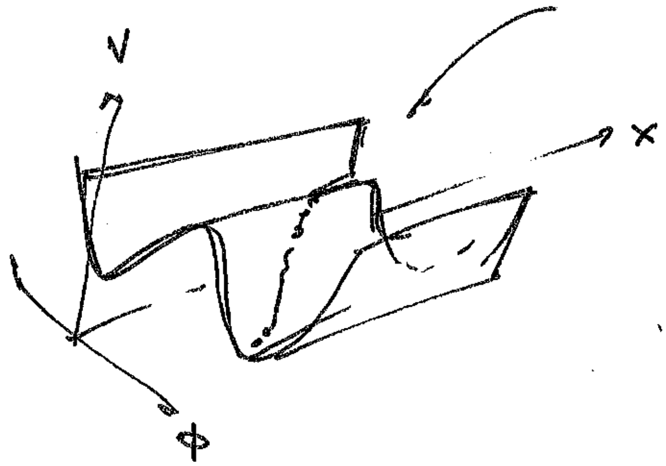
to make sense, need $\mathcal{L} = + m^2\phi^2 - \lambda\phi^4$



note: $\langle q \rangle = \pm q_0$
CAN BREAK symmetries if q was quantum #!

equivalent, but distinct vacua.

$$\mathcal{L} = (\partial_0\phi)^2 - (\partial_i\phi)^2 + m^2\phi^2 - \lambda\phi^4$$



IF YOU TRY TO PULL INTO OTHER VACUUM, YOU COST ENERGY HERE.

EC?

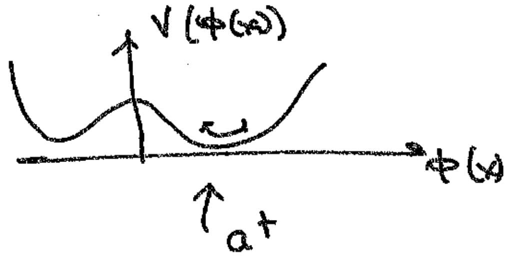
so: $\mathcal{L}[\phi]$ can have <u>ground state</u> where minimum energy config has $\langle \phi \rangle \neq 0$

↑ scalar field

ie springs are "compressed"

→ the field is classically non-zero.

→ particles are excitations about the ground state



IF ϕ HAS QUANTUM #'s, these symmetries are <u>SPONTANEOUSLY BROKEN</u>.

↑ $\mathcal{L}$ IS COMPOSED OF INVARIANTS. BUT VACUUM IS <u>NOT</u> INVARIANT.

eg.

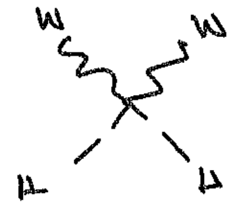
$$\mathcal{L}[H] = +m^2 |H|^2 - \lambda |H|^4$$

s.t. $\langle H \rangle = v/\sqrt{2}$.

so: $$H(x) = \underset{\langle H \rangle}{\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}} + \underset{\text{excitations about vacuum}}{\begin{pmatrix} H^1(x) \\ H^2(x) \end{pmatrix}}$$

nb $\partial \langle H \rangle = 0$

GO BACK TO LAGRANGIAN:



$\leftarrow$ from $g^2 |W^A T^A H|^2$

$$g^2 \left| W^A T^A \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \right|^2$$

$$\to g^2 W^A W^A \cdot \frac{v^2}{2} \cdot \frac{1}{2}$$

$$\to \underbrace{\boxed{\frac{g^2 v^2}{4}}}_{M_W^2} (W^2)$$

BREAKING OF GAUGE SYMMETRY GAVE MASS TO W.

↳ & ALSO B, & MASS MIXING BETWEEN THEM.