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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

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College on Computational Physics

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Computational Studies of High Energie Particles

R. Singleton

Boston University
Boston, USA

The Standard Model

1. Electromagnatism
2. Weak Interactions
3. Strong Interactions

$$\left.\begin{array}{l}\text{1. Electromagnatism}\\ \text{2. Weak Interactions}\end{array}\right\}\text{Electroweak}$$

GUTs

$$\left.\begin{array}{l} n \to p + e + \nu \\ \pi \to \mu + \nu \quad \ldots \\ \Xi \quad \Lambda \quad \rho \quad \Upsilon \quad \ldots \end{array}\right\} \text{particle zoo}$$

Who ordered that?

(what about simplicity?)

leptons: $e \quad \nu_e \quad \mu \quad \nu_\mu \quad \tau \quad \nu_\tau$

e: 0.5 MeV, μ: 105 MeV, τ: 1.5 GeV

quarks: $u \quad d \quad c \quad s \quad t \quad b$

u: MeV, t: 170 GeV (CDF at FNAL)

Hadrons (composed of quarks)

Mesons ($q\bar{q}$)

π
ρ
η
$\vdots$

Baryons (qqq)

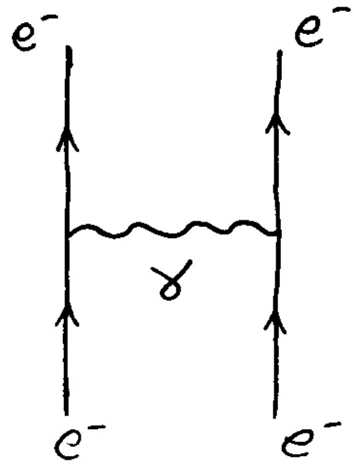
$p \quad n$
Λ
Ω
Ξ
$\vdots$

leptons: $\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$ $\begin{matrix} Q=-1 \\ Q=0 \end{matrix}$

quarks: $\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$ $\begin{matrix} Q=\frac{2}{3} \\ Q=-\frac{1}{3} \end{matrix}$

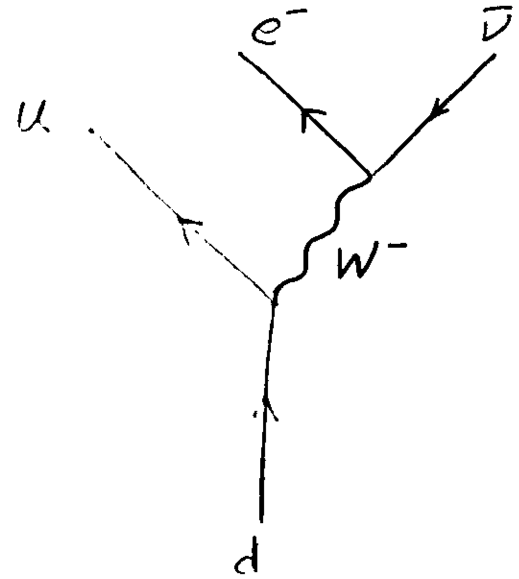
strongly interacting $\longrightarrow$ heavier $S=\frac{1}{2}$

1. electromagnetic



photon: $m_\gamma = 0$

2. Weak

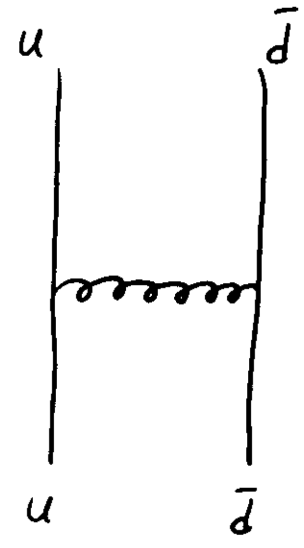


W boson: $m_W \cong 80\,\text{GeV}$

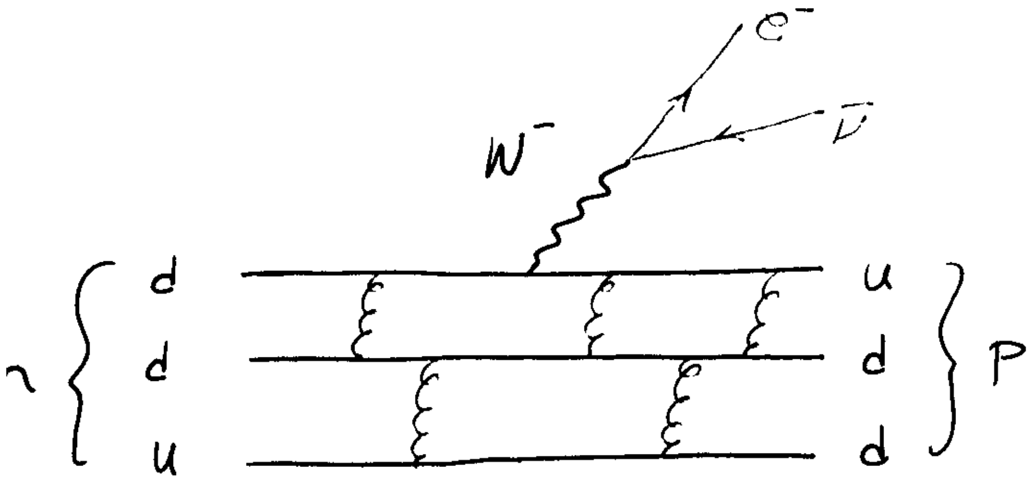
(cf. proton $\approx 1\,\text{GeV}$)

Z boson: $m_Z \cong 90\,\text{GeV}$

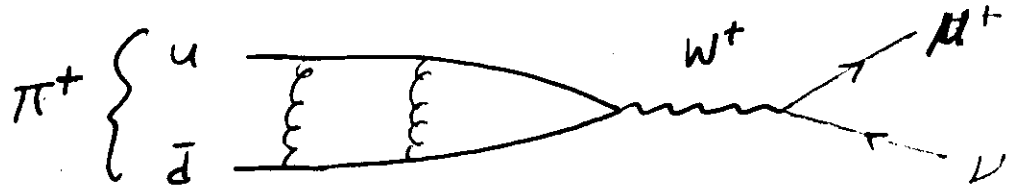
3. Strong



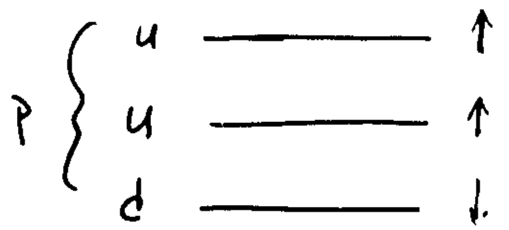
gluon: $m_g = 0$



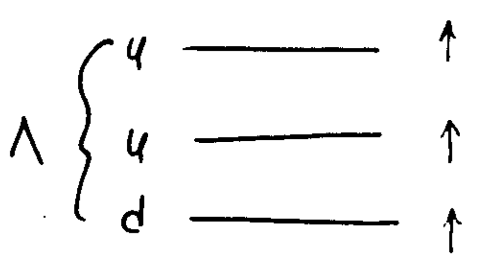
$n \to p e \bar{\nu}$



$\pi^+ \to \mu^+ \nu$



$S = \frac{1}{2}$



$S = \frac{3}{2}$

Symmetry

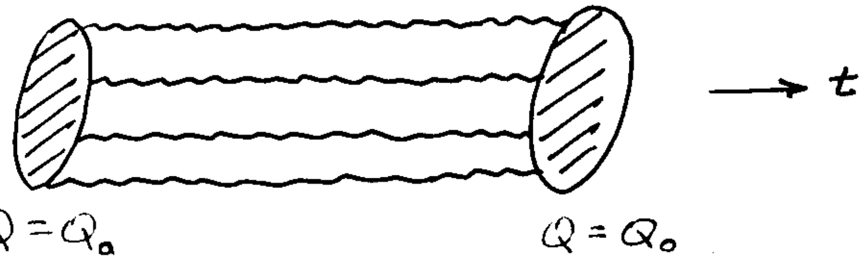
- Global
  - non-broken
  - spontaneously broken (hidden)
- Local (gauge)
  - non-broken
  - broken (Higgs mechanism)

Hidden symm.

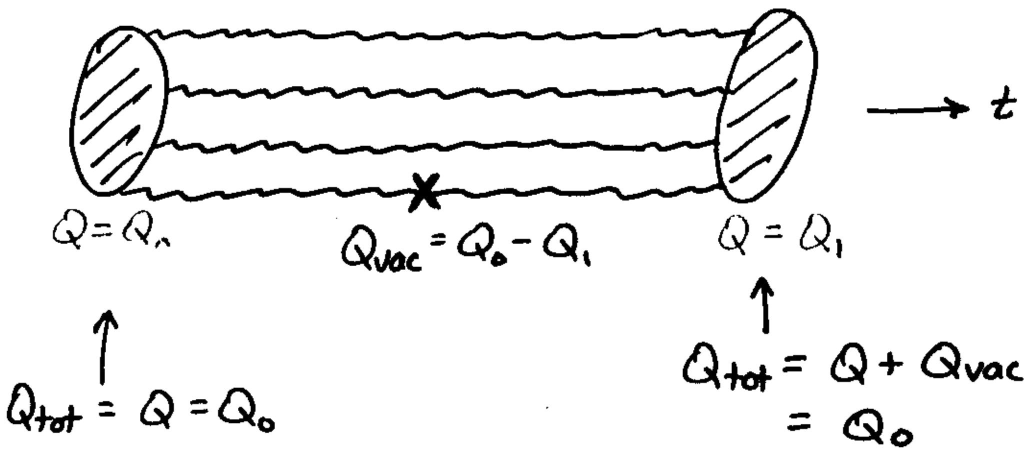
charged vacuum

symmetry $\Rightarrow$ "charge" conservation

e.g. $\psi(x) \rightarrow e^{i\theta}\psi(x)$ $\Rightarrow$ electric charge conservation non-broken:



broken:



If you only look at Q of system, it appears that charge is not conserved.
(Hidden symmetry)

Isospin (global):

$$\begin{pmatrix} p \\ n \end{pmatrix} \longrightarrow \begin{pmatrix} p' \\ n' \end{pmatrix} = \underset{\substack{\uparrow \\ SU(2)\ \text{matrix}}}{U} \begin{pmatrix} p \\ n \end{pmatrix}$$

p & n are the "same" (up to electromag.)
e.g. $m_u \cong m_d$ (broken by electromag.)

Electromagnatism (local):

$$\psi(x) \rightarrow e^{i\theta(x)}\,\psi(x)$$

$$A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu \theta(x)$$

$\uparrow$ compensating field: $A_0 = \varphi$ (potential)
$\underline{A}$ (vector potential)

$m_\gamma = 0$ (gauge symm.)

Can we unify weak and electromagnetic?

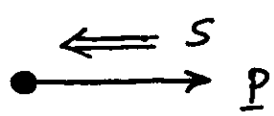
Problems

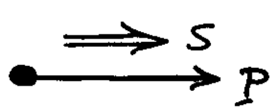
1. Gauge boson masses

$$\left.\begin{aligned} M_W &\cong 80 \text{ GeV} \\ M_Z &\cong 90 \text{ GeV} \\ M_\gamma &= 0 \end{aligned}\right\} \leftarrow \text{non-gauge interaction}$$

2. Fermion masses

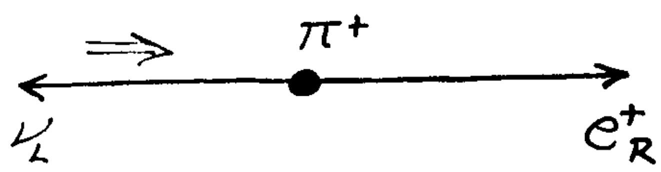
weak interactions are left handed.

L 

R 

$\nu \quad (m_\nu = 0)$

Pairity Violation (Cheng + Lee): the universe is Left handed.



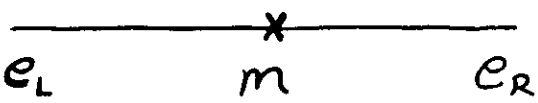
The L handed particles are charged:

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \longrightarrow U \begin{pmatrix} u \\ d \end{pmatrix}_L$$

The R handed particles are neutral:

$$\begin{pmatrix} u \\ d \end{pmatrix}_R \longrightarrow \begin{pmatrix} u \\ d \end{pmatrix}_R$$

mass allows for the change
of orientation:



In a chiral (handed) theory, symmetry requires that all fermions are massless!

How do we make the weak interactions into a gauge theory?!?

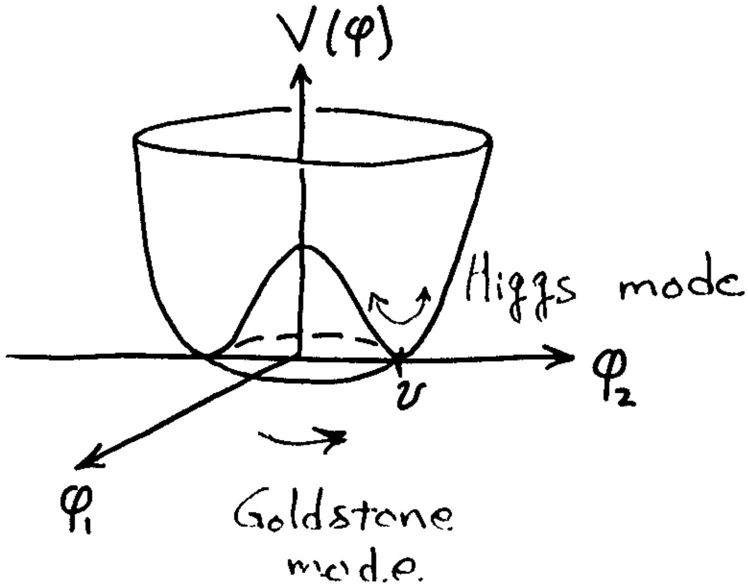
1. Gauge Boson masses ← I will discuss
2. Fermion masses ← Will not have time to discuss

note: I bring up chirality + fermions here because in Lecture II this will be cruitial.

The Higgs Mechanism

Locally broken symmetry solves both the probems of gauge boson masses and chiral fermion masses.

scalar field φ: $s=0$



π : massless Goldstone excitation

h : massive Higgs excitation

note: the vacuum is $|\varphi| = v$. The vacuum is thus charged if φ is charged.

$\therefore$ Spontaneous symm. breaking.

$m_W = 0 \Rightarrow 2\,T$ W modes

$m_W \neq 0 \Rightarrow 2\,T + L$ W mode

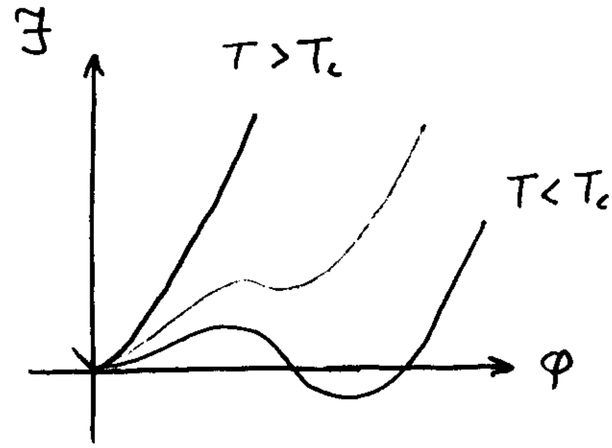
We can steal the goldstone mode and convert it to the L W component.

$$\underbrace{W:\ 2\,T \qquad \varphi:\ \pi}_{2T + L \ (m_W \neq 0)} \quad h$$

A prediction: a residual scalar particle (s=0).

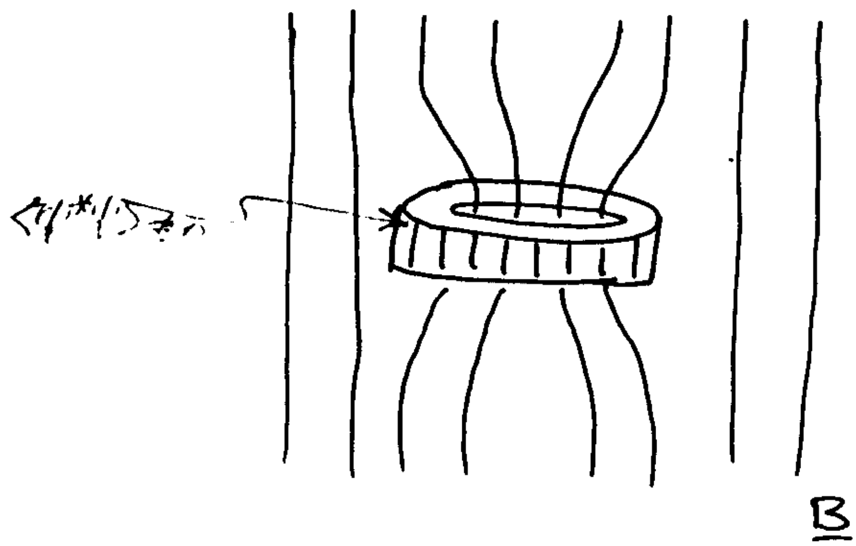
The W is said to "eat" the goldstone boson.

This is all very familar: G-L theory of super. cond.



$\varphi = \langle \psi^* \psi \rangle \leftarrow$ cooper pairs.

$\varphi \neq 0 \Rightarrow$ Meisner effect:



The photon field becomes short range and is expelled from the S.C. medium.

The Standard Model

$$SU(2)_L \times U(1)_Y$$

$$SU(2)_L \;\begin{cases} W^+ \\ W^- \\ W^0 \end{cases}$$

$$U(1)_Y \;—\; B$$

$$\left.\begin{matrix} W^0 \\ B \end{matrix}\right\} \begin{matrix} Z^0 \\ A \end{matrix}$$

$$\boxed{M_W = \cos\theta \, M_Z}$$