

Overview

Four forces in nature

- Electromagnetism → process between charged particles
 $e^- \rightarrow e^- + \gamma$
- Weak force → β decay $n \rightarrow p + e^- + \bar{\nu}_e$
- Strong force → between n/p constituents are bounded by the strong force
- Gravitational force
→ between celestial objects.

→ electromagnetism, weak & strong force can be explained by fundamental theories, which is known as standard Model of particle physics. (1970s)

(SM)

→

→ consistent and calculable quantum theory, can explain the interaction between different particles except gravity

→ the theory has been tested experimentally at various high energy and low energy experiments

→ Can be embedded into a more general theory such as supersymmetry, GUT, string theory.

#

Structure of SM

SM is based on QFT

- Lagrangian depends on fields, electron, photon, other particles correspond to the respective fields $\psi(\vec{x}, t)$ and their derivatives.
- particles are quanta of these fields, particles can have different spin, masses, other quantum numbers.
- * Every relativistic quantum field theory, including SM, is constructed to respect $(E, \vec{p})$ conservation, is Lorentz invariant {collectively Poincare invariant}
- The interaction is governed by gauge principles (such as QED)

often encounters $(\bar{\psi} \gamma^M \psi) A_\mu$ type of terms.

- unlike QED, ~~the~~ SM is based on non-abelian gauge theory, QED can be retrieved from full SM theory

The fundamental quanta of SM determines all the stable and unstable particle excitations.

⑤

particle content of the SM

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Matter part

mediators of the forces

↓
Gauge bosons

① leptons ② quarks Higgs

- ① leptons → simplest constituents of the SM.
 → spin $\frac{1}{2}$ particles/fields
 → 3 generations of leptons

① Electron generation

$SU(2)_L$
doublet

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

$$e_R^-$$

e_L and e_R of Dirac field e is treated differently

② Muon

$$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$$

$$\mu_R^-$$

③ Tau

$$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$\tau_R^-$$

→ neutrinos are electromagnetically uncharged, do not interact with photon, e^- , μ^- & τ^- are -ve charged. each has its own antiparticle. They are the Dirac spinors, 4 component object

→ $\psi_D = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix} = \psi_L + \psi_R$

$\begin{pmatrix} \psi_1 \\ \psi_2 \\ 0 \\ 0 \end{pmatrix}$ → Left handed piece

$\begin{pmatrix} 0 \\ 0 \\ \psi_3 \\ \psi_4 \end{pmatrix}$ → right handed piece

→ concept of chirality

→ $e = e_L + e_R$

$e_L = \frac{1}{2}(1 - \gamma_5) e$

$e_R = \frac{1}{2}(1 + \gamma_5) e$

γ_5 is the operator $\gamma_5^2 = 1$

→ projection operator

→ e_L & e_R are eigenstates of γ_5 with eigenvalue ∓ 1 , i.e.

$\gamma_5 e_L = -e_L$

$\gamma_5 e_R = +e_R$

→ For massive particle, $\frac{ev}{-1}$ is -ve helicity

$\frac{ev}{+1}$ is +ve helicity

→ no γ_R in the SM, as neutrinos have been treated massless in SM. A mass term for a spin $\frac{1}{2}$ Dirac field will require both L & R component.

Ex-1

$$\psi_{L,R} = \frac{1}{2} (1 \mp \gamma_5) \psi$$

$$\psi_{L,R}^\dagger = \frac{1}{2} \psi^\dagger (1 \mp \gamma_5)$$

a) Show that the Dirac mass term for electron mixes both L & R component.

b) Verify the kinetic term or the derivative term of the Dirac Lagrangian is a sum of L + R terms.

→ the fact that L & R components have been treated differently in SM ~~shows~~ is due to lack of parity symmetry

lepton in SM interacts only through electromagnetic & weak interactions.

In fact neutrinos interact only via weak interactions

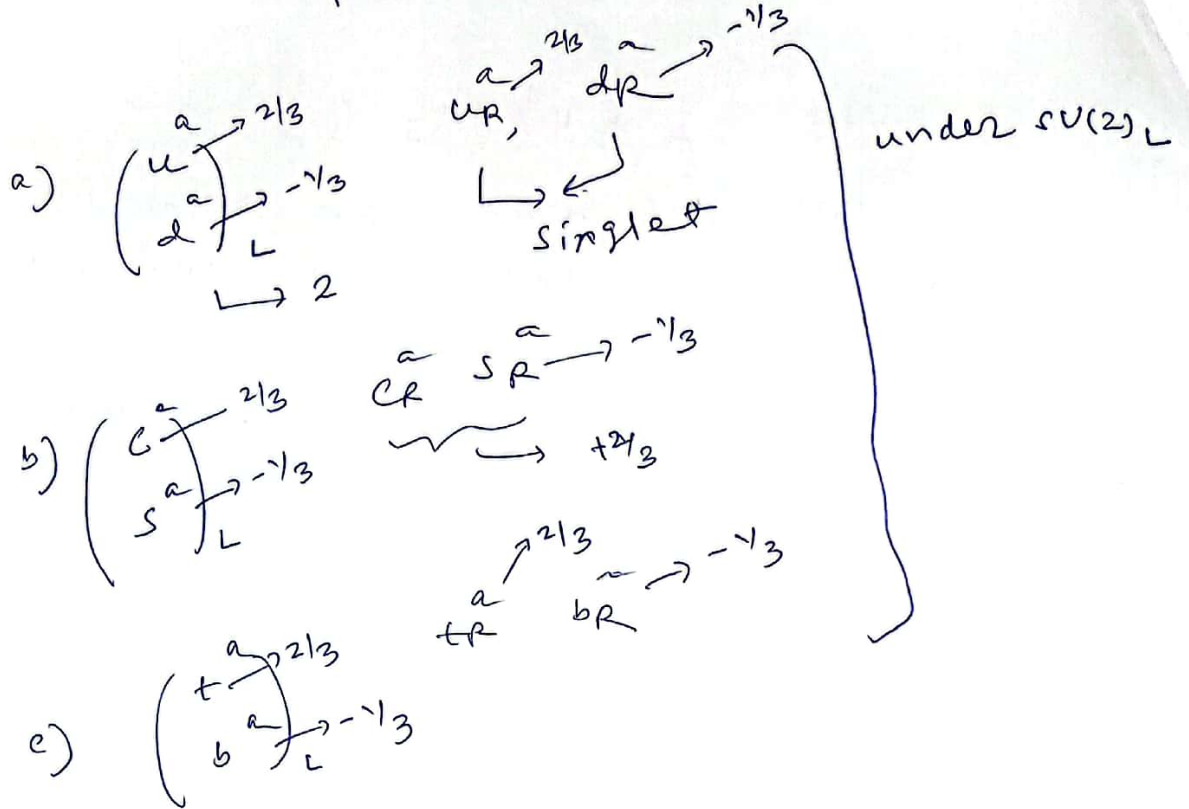
$$m(e) = 0.5 \text{ MeV}$$

$$m_\mu = 105 \text{ MeV}$$

$$m_\tau \approx 1.7 \text{ GeV}$$

② quarks - spin $\frac{1}{2}$ objects

3 families



$a = 1, 2, 3 \rightarrow$ color index
 $\rightarrow$ quarks have color charge,
 triplets under $SU(3)_c$

Difference from the lepton sector

- $\rightarrow$ we have right handed components for both the members of a doublet
- $\rightarrow$ quarks carry charge under an additional gauge interaction $SU(3)_c$. Each quark has a color index $a = 1, 2, 3$
- $\rightarrow$ EM charge are different for u quark and down quark.

quarks are not found as free particles in nature, always in bound state $\Rightarrow$ confinement

$$\frac{u, d}{\bar{q}q} \rightarrow \text{meson}$$

$$qqq \rightarrow \text{baryon}$$

asymptotic freedom

$$\left[\begin{array}{lll} m_u \sim 2 \text{ MeV} & m_c \sim 1.3 \text{ GeV} & m_b \sim 4.2 \text{ GeV} \\ m_d \sim 4.79 \text{ MeV}, & m_s \sim 92 \text{ MeV}, & m_t \sim 173 \text{ GeV} \end{array} \right]$$

③ Gauge bosons $\rightarrow$ spin 1 field
(vector boson)

a) $A_\mu \rightarrow$ massless particle, mediator of electromagnetic interactions, neutral under all interactions.

b) electroweak bosons $\rightarrow W_\mu^\pm, Z_\mu^0$
 $\rightarrow$ weak interaction mediator

- $\rightarrow$ neutral under strong interaction
- $\rightarrow$ electromagnetic charged $W_\mu^\pm$
- $\rightarrow$ charged under weak interaction
- $\rightarrow$ They interact among themselves through weak interactions

$$W_\mu^+ W_\mu^- A_\mu, W W Z \text{ etc.}$$

$$M_H = 80.4 \text{ GeV} \\ .36 \\ M_Z \sim 91 \text{ GeV} \\ .18$$

(c) Gluons a_b

- 8 gluons, massless
- they do not appear as free particles due to the strong force
- Mediates strong interaction, also charged under strong interaction, neutral under electroweak interaction

(4) Higgs → spin 0, electromagnetically neutral

$$m_H \sim 125.11 \pm 0.11 \text{ (ATLAS)} \\ 125.35 \pm 0.15 \text{ (CMS)}$$

$$L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \rightarrow Y_L = -1 \quad \psi(x) \rightarrow \psi'(x) \\ e_R \rightarrow Y_R = -2 \quad = e^{i\alpha Y/2} \psi$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_H = +1$$

$$t \sim 173 \text{ GeV} \\ b \sim 4.5 \text{ GeV} \quad \left(\begin{matrix} u & c \\ d & s \end{matrix} \right) ?$$

$$Q = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$T_3 + Y/2 \Rightarrow$$

$$Y/2 = 2(Q - T_3) \\ = 2/3 - 1 = -1/3 \\ = -2/3 + 1 = 1/3$$

$$Y(u_R) = 2/3 \\ Y(d_R) = -1/3$$

$$2 - 1/3 =$$

Strong interaction $\rightarrow$ force which holds nucleons together ~ 1 $\sim$ range $\sim 10^{-15} \text{ m}$

particles
 $\frac{\text{allion, quarks, nucleons}}{\text{particles}}$

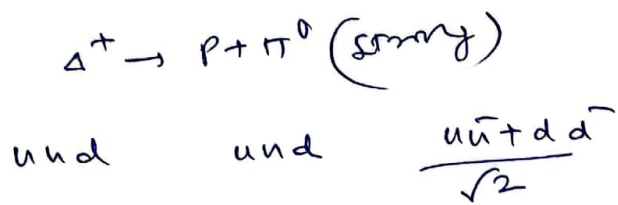
Electromagnetic $\rightarrow$ force between charge particle

$\sim 1/137$

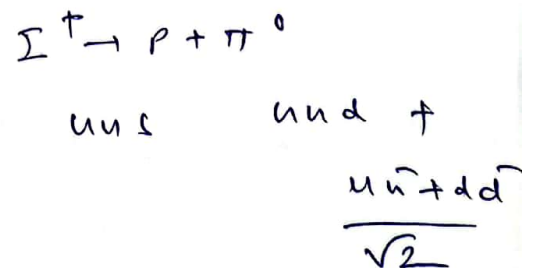
Weak $\rightarrow n \rightarrow p + e^- + \bar{\nu}_e$ $\sim$ strength 10^{-6}
 $\sim$ range 10^{-18} m

Gravity $\sim$

strength $\sim 10^{-39}$
 $\sim$ infinite



$$\tau = 6 \times 10^{-24} \text{ s}$$



$$\tau = 8 \times 10^{-11} \text{ s}$$

$$\frac{\alpha_H}{\alpha_S} \approx \sqrt{\frac{\tau_\Delta}{\tau_\Sigma}} \sim 2.7 \times 10^{-7}$$

$$\alpha_H \sim 10^{-6} - 10^{-7}$$

Some of the units

1) Length : $1 \text{ fm} \approx 10^{-15} \text{ m}$
 $\sim$ roughly the size of a proton

2) Mass/Energy scale : set by the rest mass/Energy of the proton

$$E_p = m_p c^2$$

$$\sim 1 \text{ GeV}$$

$$1 \text{ GeV} = 10^9 \text{ eV}$$

$$1 \text{ MeV} = 10^6 \text{ eV}$$

$$1 \text{ KeV} = 10^3 \text{ eV}$$

$$1 \text{ TeV} = 10^{12} \text{ GeV}$$

3) Natural units

$$\hbar = 1, c = 1$$

Mass measured in units of energy

$$M = \frac{E}{c^2} \sim \text{GeV}$$

$$\text{length} = \frac{\hbar}{Mc} = (\text{GeV})^{-1}$$

$$(1 \text{ GeV})^{-1} \approx 0.2 \text{ fm}$$