Overview

Four fources in nature

- → electromagnetism → process between charged particles
  $e^- \to e^- + \gamma$
- → weak force → β decay $n \to p + e^- + \bar{\nu}_e$
- → 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. (1970)

(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 $(\bar{\psi}\gamma^{\mu}\psi) A_{\mu}$ 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.

(B)

particle content of the SM

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

- Matter part
  - (1) leptons
  - (2) quarks
  - Higgs
- mediators of the forces
  - Gauge bosons

(1) leptons

→ simplest constituents of the SM.

→ spin $1/2$ particles | fields

→ 3 generation of leptons

(A) Electron generation		(B) Muon	(3) Tau
$SU(2)_L$ doublet $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	e_L and e_R of Dirac field e is treated differently	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$
e_R^-		μ_R^-	τ_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 spinor, 4 component object

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

$\begin{pmatrix} \psi_1 \\ \psi_2 \\ \hline 0 \end{pmatrix} + \begin{pmatrix} 0 \\ \hline \psi_3 \\ \psi_4 \end{pmatrix} \rightarrow$ right handed piece

$\rightarrow$ Left handed piece $\rightarrow$ concept of chirality

$\rightarrow$ $e = e_L + e_R$

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

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

γ_5 is the operator $\gamma_5^2 = 1$

$\rightarrow$ projection operator

$\rightarrow$ e_L & e_R are eigenstates of γ_5 with eigenvalue ∓ 1, i.e $\gamma_5 e_L = -e_L$

$\gamma_5 e_R = +e_R$

$\rightarrow$ For massive particle, ev $= -1$ is $-$ve helicity

ev $= +1$ is $+$ve helicity

$\rightarrow$ no ν_R in the SM, as neutrinos have been treated massless in SM. A mass term for a spin ½ dirac field will require both L & R component.

Ex-1

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

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

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

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lepton in SM interacts only through electromagnetic & weak interactions.

In fact Neutrinos interact only via weak interactions

$m(e) = 0.5$ MeV

$m_\mu = 105$ MeV

$m_\tau \approx 1.7$ GeV

② Quarks - spin $\frac{1}{2}$ objects

3 familes

a) $\begin{pmatrix} u^a \\ d^a \end{pmatrix}_L$ — $u^a \to 2/3$, $d^a \to -1/3$; $\to 2$

$u^a_R \to 2/3$, $d^a_R \to -1/3$ $\to$ singlet

b) $\begin{pmatrix} c^a \\ s^a \end{pmatrix}_L$ — $c^a \to 2/3$, $s^a \to -1/3$

c^a_R, $s^a_R \to -1/3$; $c^a_R \to +2/3$

c) $\begin{pmatrix} t^a \\ b^a \end{pmatrix}_L$ — $t^a \to 2/3$, $b^a \to -1/3$

$t^a_R \to 2/3$, $b^a_R \to -1/3$

under $SU(2)_L$

$a = 1, 2, 3 \to$ color index

$\to$ quarks have color charge, triplets under $SU(3)_c$

Difference from the lepton sector

→ we have right handed components for both the members of a doublet

→ quarks carry charge under an additional gauge interaction $SU(3)_c$. Each quarks has a color index $a = 1, 2, 3$

→ EM charge are different for u quark and down quark.

quarks are not found a free particles in nature, always in bound state ⟹ confinement & asymptotic freedom

e.g $\bar{q}q \to$ Meson

$qqq \to$ baryon

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

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③ Gauge bosons → spin 1 field (vector boson)

a) A_μ → Massless particle, mediator of electromagnetic interactions, neutral under all interactions.

b) electroweak bosons → $W_\mu^\pm$, Z_μ^0

→ weak interaction mediator

→ Neutral under strong interation

→ electromagnetic charged $W_\mu^\pm$

→ charged under weak interaction

→ They interact among themselves through weak interactions

$W_\mu^+ W_\mu^- A_\mu$, WWZ etc.

$M_W = 80$ GeV
$\cdot 36$
$M_Z \sim 91$ GeV
$\cdot 18$

(c) Gluons G_μ^{ab}

→ 8 gluons, massless
→ they do not appear as free particle due to the strong force
→ Mediates strong interaction, also charged under strong interaction
Neutral under electroweak interaction

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(4) Higgs → spin 0, electromagnetically neutral

$m_H \sim 125.11 \pm 0.11$ (ATLAS)
125.35 ± 0.15 (CMS)

$L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \longrightarrow Y_L = -1$ $\quad \psi(x) \to \psi'(x)$

$e_R \longrightarrow Y_R \Rightarrow -2$ $\quad = e^{i\alpha Y/2}\psi$

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

$t \sim 173$ GeV
$b \to 4.5$ GeV $\Big\}$ $\begin{matrix} u & c \\ d & s \end{matrix}$?

$q = \begin{pmatrix} u \\ d \end{pmatrix}_L$ $\quad T_3 + Y/2 \Rightarrow$ $\quad Y/2 = 2(Q - T_3)$

$= 4/3 - 1 = 1/3$

$= \cancel{\ } - 2/3 + 1 = 1/3$

$Y(u_R) = 4/3$

$Y(d_R) = -2/3$

$2 - 1/3 -$

Stronginteraction → force which holds nucleus together ~ 1 ~ range ~ 10^{-15} m

particles

gluon, quarks, nucleons

Electromagnetic → force between charge particle

~ 1/137

Weak → $n \to p + e^- + \bar{\nu}_e$ ~ strength 10^{-6}

~ range 10^{-18} m

Gravity ~> strength ~ 10^{-39}

~ infinite

$\Delta^+ \to p + \pi^0$ (strong)

uud uud $\frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$

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

$\Sigma^+ \to p + \pi^0$

uus uud + $\frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$

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

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

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

Some of the Units

1) Length : 1 fm = 10^{-15} m
~ 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

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

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

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