NUCLEAR & PARTICLE PHYSICS 2015

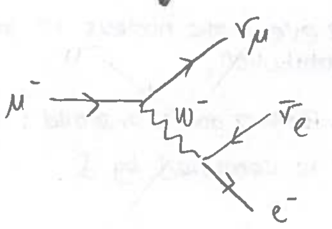
① Fundamental leptons in SM : e^-, μ^-, τ^- ; ν_e, ν_μ, ν_τ

stable (e^-) ; μ^-, τ^- → unstable ; ν_e, ν_μ, ν_τ → stable

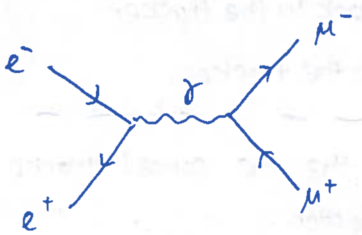
$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$
or
$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

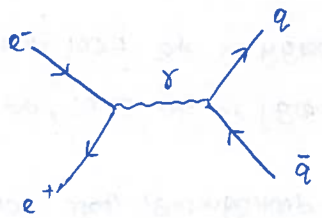
$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$

$\tau^+ \to \mu^+ + \nu_\mu + \bar{\nu}_\tau$



② (a). Find the ratio of the cross-section for $e^+e^- \to$ Hadrons $(q\bar{q})$ the cross-section for $e^+e^- \to \mu^+\mu^-$.





- The possible quark-antiquark final states are $u\bar{u}$, $d\bar{d}$, $c\bar{c}$, $s\bar{s}$, $b\bar{b}$ (Not including the $t\bar{t}$ because the $\sqrt{s} \sim 30$ GeV only)

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{\sigma(u\bar{u}) + \sigma(d\bar{d}) + \sigma(c\bar{c}) + \sigma(s\bar{s}) + \sigma(b\bar{b})}{\sigma(\mu^+\mu^-)}$$

$$= N_c \times \frac{\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2}{1^2} = \frac{11}{9} N_c$$

Quarks have an additional DOF → Colour DOF

- Experimental value is $\sim \frac{33}{9}$. $\therefore N_c = 3$.

(b) Strong force → short range.

- Hadronization takes place at separations of about 1 fm.
- At this point, the forces are those between colourless hadrons and the associated exchanged particles must therefore be colourless.

Strong force is short range force because it is mediated by gluons. Gluons carry colour charge and therefore self interact.

(5)

6) (a) - The coupling of the Higgs boson depends on the mass of the particle.

- It is most likely to decay to the heaviest particles ~~that~~ is kinematically allowed to decay to.
- Since the mass of the Higgs Boson is $M_H = 125\ GeV/c^2$, if a Higgs is produced with this invariant mass, there wouldnot be enough energy to create two top quarks (each with a mass of $M_t = 175\ GeV/c^2$.)
- The heaviest particle with a mass less than half the Higgs mass is the bottom quark.

For that reason, the ~~heaviest particle with a mass less than half the Higgs mass~~ dominant decay of the Higgs boson is to a $b\bar{b}$ pair.

(b) • Mass of $W \rightarrow 80\ GeV/c^2$

• Even though $M_H < 2M_W$, if one of the W bosons is produced with a mass less than M_W (allowed for virtual particles), then the Higgs decay to W^+W^- pair is possible, but suppressed.

• If $M_H > 2M_W$, there would be enough energy to create W^+W^- pair, therefore, the branching fraction to a W^+W^- pair would be larger.

(c) → Extremely large background

→ Poor resolution of the jets coming from the bottom quarks, making a peak in the dijet invariant mass difficult to resolve.

(II) b-quarks $\xrightarrow{\text{hadronise}}$ B-mesons

(carry 70% of the energy of the primary b-quark)

mean life-time of B-mesons $\rightarrow$ 1.5 ps

$\rightarrow$ Distance travelled before decaying:

Decay length : $\boxed{L = \gamma c \tau}$

$$\gamma = \frac{0.7 \times 68 \text{ GeV}}{5.0 \text{ GeV}/c^2} \leftarrow \frac{E}{mc^2}$$

$$= 9.52$$

$$L = (9.52)(3\times10^8)(1.5\times10^{-12})$$

$$L = 4.284\times10^{-3} \text{ m}$$

$\hbar = c = 1$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\beta = \sqrt{1-\frac{1}{\gamma^2}}$$

$$\gamma = \frac{E}{mc^2} = \frac{E}{m}$$

$$\gamma\beta = \frac{pc}{mc^2} = \frac{p}{m}$$

$$\beta = \frac{pc}{E} = \frac{p}{E}$$

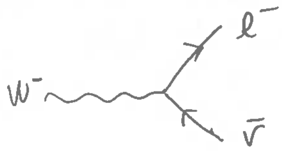
(III) One of the W bosons decay leptonically (to an electron / muon)

The other decays hadronically.

CHECK!

$W^+ \rightarrow \ell^+ \nu$

$W^- \rightarrow \ell^- \bar{\nu}$



$W^+ \rightarrow q\bar{q}$

$W^- \rightarrow q\bar{q}$

Assuming either W^+ or W^-.

Total no. of jets $\Rightarrow$ There will be 2 jets (because of the quarks & antiquarks).

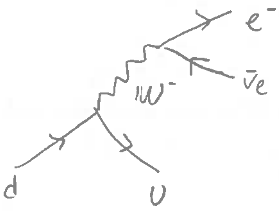
charged lepton $\Rightarrow$ 1 charged lepton.

(IV) Identified by their tracks and the energy deposits in the calorimeter(HCAL).

NOT ENOUGH FOR 3 MARKS

(8) (a)(I) differential decay rate → $\frac{dw}{dE_e} \propto P_\nu E_\nu$

Beta decay: $\beta^- \Rightarrow n \to p + e^- + \bar{\nu}_e$



assumption: neutrino is massless

- $E^2 = p^2c^2 + m^2c^4$

$E_\nu = \sqrt{P_\nu^2 c^2 + m_\nu^2 c^4}$

- for massless neutrino,

$E_\nu = P_\nu c$

In natural units,

$E_\nu = P_\nu$

$E_\nu^2 = P_\nu E_\nu$

Given $E_0 = E_e + E_\nu$

Rearrange, $E_\nu = E_0 - E_e$

$E_\nu^2 = (E_0 - E_e)^2$

$\frac{dw}{dE_e} \propto P_\nu E_\nu$

$\frac{dw}{dE_e} \propto E_\nu^2$

$\frac{dw}{dE_e} \propto (E_0 - E_e)^2$

(II) Why can the nuclear recoil energy be assumed to be negligible?

$E_0 = (\Delta m)c^2$

↳ Δm : neutron-proton mass difference

Total energy released ← $E_0 = \underbrace{E_e}_{\text{total energy of electron}} + \underbrace{E_\nu}_{\text{Total energy of neutrino}} + E_{recoil} \sim E_e + E_\nu$

→ We consider the neutron and proton to be 'heavy', so that they have negligible kinetic energy, and all the energy released in the decay process goes into creating the electron and neutrino and in giving the KE.

(III) Write an expression for $\frac{dw}{dE_e}$ (assumption: finite neutrino mass, m_ν)

$\frac{dw}{dE_e} \propto (E_0 - E_e)^2$

$E^2 = p^2c^2 + m^2c^4$ ⟶

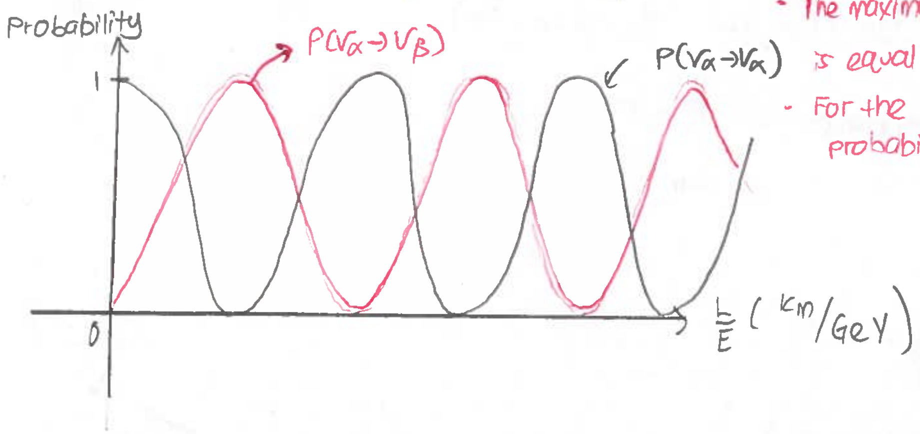
$E_0 = \sqrt{P_0^2c^2 + m_0^2c^4}$

$E_e = \sqrt{P_e^2c^2 + m_e^2c^4}$

(9) (a) (I) $P(\nu_\alpha - \nu_\beta) = \sin^2(2\theta)\sin^2\left[1.27\ \frac{\Delta m^2 L}{E}\right]$ $\Delta m^2 = m_2^2 - m_1^2$

Sketch $P(\nu_\alpha \to \nu_\beta)$ and $P(\nu_\alpha \to \nu_\alpha)$ as a function of $\frac{L}{E}$ for $\theta = 45^\circ$.

For $\theta = 45^\circ$, $P(\nu_\alpha \to \nu_\beta) = \sin^2\left[1.27\ \Delta m^2\ \frac{L}{E}\right]$



- The maximum probability of conversion is equal to $\sin^2 2\theta$.
- For the case of $\theta = 45^\circ$, The max. probability of conversion is 1.

Black curve → probability of the original neutrino retaining its identity.

Red curve → probability of conversion to the other neutrino.

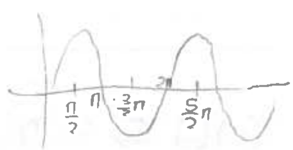
(II) distance between the neutrino source and the far detector → 1300 km

$\Delta m^2 = 2.43 \times 10^{-3}\ eV^2$

Find the largest and next to largest energy for which the oscillation probability $P(\nu_\alpha \to \nu_\beta)$ is maximised.

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left[1.27\ \frac{\Delta m^2 L}{E}\right]$$

For max. oscillation probability, $P(\nu_\alpha \to \nu_\beta) = 1$



$$\sin^2\left(1.27\ \frac{\Delta m^2 L}{E}\right) = 1$$

$$\sin\left(1.27\ \frac{\Delta m^2 L}{E}\right) = 1$$

$$1.27\ \frac{\Delta m^2 L}{E} = \frac{\pi}{2}, \frac{3}{2}\pi, \frac{5}{2}\pi$$

For $\frac{\pi}{2}$, $E_1 = 2.554..\ GeV$

$\frac{3\pi}{2}$, $E_2 = 0.8513..\ GeV$.

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2\left(E_\pi - \sqrt{E_\pi^2 - m_\pi^2}\right)}$$

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2\left(E_\pi - E_\pi + \frac{1}{2}\frac{m_\pi^2}{E_\pi}\right)}$$

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{\frac{m_\pi^2}{E_\pi}}$$

$$\boxed{\frac{E_\nu}{E_\pi} = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2}}$$

(II) $E_\nu = 3\,GeV$

$m_\pi = 140\ MeV/c^2$

$m_\mu = 106\ MeV/c^2$

$$E_\pi = \left(\frac{m_\pi^2}{m_\pi^2 - m_\mu^2}\right) E_\nu$$

$$= (2.343\ldots) E_\nu$$

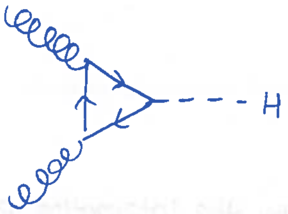
$$E_\pi = 7.0301\ldots\ GeV$$

(d) (I) ~~Eo~~ Charged current interaction

Without specifying the hadronic final state ? (Dafuq!)

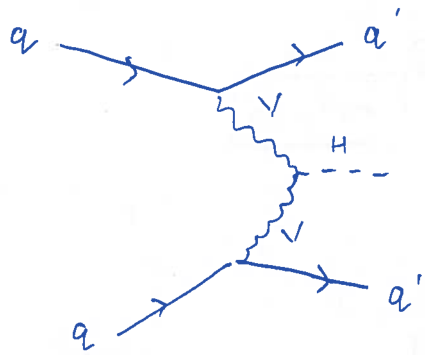
(II) electrons & muons have characteristic signatures in particle detectors. They 'flavour-tag' the ~~neutrion~~ neutrino (If an electron is produced, it come from an electron neutrino).

(10) (a) (I) Gluon-gluon fusion



- Gluons have 0 mass
- Do not couple directly with the Higgs
- Process occurs via a quark loop (usually top quark as it is the heaviest

(II) Vector boson fusion

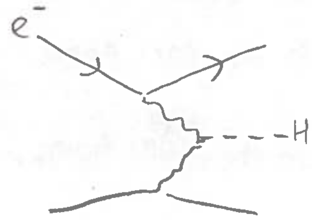


- Either a $W^{\pm}$ or a Z boson is radiated from a quark from each proton
- Then, either a W^+W^- or a ZZ pair fuse to form a Higgs.

(III) associated W/Z Higgs production. (Higgsstrahlung)

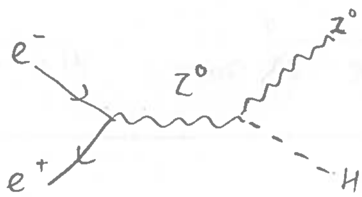
- A virtual $W^{\pm}$ or Z boson is produced by quark-antiquark annihilation, and the boson radiates a Higgs boson.

(b) $V \rightarrow W^{\pm}$ in the vector boson fusion :



✓ CHECK!

$V \rightarrow Z^0$ in the Higgstrahlung :



(c) mathematically : $s = (P_1 + P_2)^2$

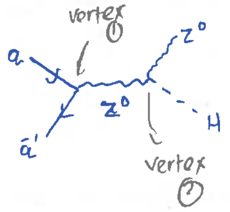
$s = P_1^2 + P_2^2 + 2P_1 \cdot P_2$

For lepton collision, $P_1^2 = P_2^2 = 0$ (mass can be neglected)

However for hadron collision (proton), mass cannot be neglected.

CM energy, $\sqrt{s} = \sqrt{P_1^2 + P_2^2 + 2P_1 \cdot P_2}$

(e)



$x = x_1 = x_2$

$m_Z = 91\ GeV/c^2 \quad (0.091\ TeV/c^2)$

At vertex 1: $\quad m_Z^2 c^4 = 4x^2 E_p^2$

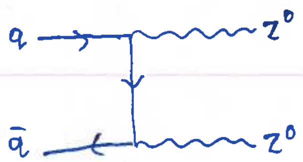
At vertex 2: $\quad 4x^2 E_p^2 = (m_Z c^2 + m_H c^2)^2$

$$x = \left[\frac{(m_Z c^2 + m_H c^2)^2}{4E_p^2}\right]^{1/2}$$

$$= \frac{m_Z c^2 + m_H c^2}{2E_p}$$

$$x = \frac{27}{1000} \,/\, 0.027$$

(f) Decay → $H \to Z^0 Z^0$



⇒ • The two Z bosons will decay to a pair of fermions. [ie. For $H \to ZZ$, $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$ ~~can~~ will form].

• If we plot the invariant mass of the four leptons in the final state, there should be a peak at the mass of the Higgs for the events coming from a Higgs ($H \to ZZ$).

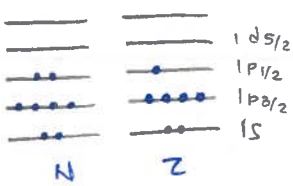
(g) Ground state $^{15}_{7}N$

$\boxed{\begin{matrix} Z = 7 \\ N = 8 \end{matrix}}$

Odd A nuclei

→ Spin of the nucleus is the j-value of the unpaired nucleon

→ Parity $= (-1)^\ell$ where ℓ is the orbital angular momentum of the unpaired nucleon.



$$J^P = \frac{1}{2}^{-1}$$