Neutrino Physics Course

Lecture I

25/4/2023

LMU
Spring 2023

Why neutrino?

Standard Model:

1. gauge principle

   = messengers

2. Spontaneous Symmetry Breaking

   (SSB)

3. Maximal violation of parity

   in weak int.

SM: $G_{SM} = U(1) \times SU(2) \times SU(3)$

$$\underbrace{\overset{\nearrow}{\text{em}} \qquad\qquad \overset{\uparrow}{\text{weak}}}_{\text{ew}} \qquad \overset{\nearrow}{\text{strong}}$$

(QCD)

= electro-weak

. em (QED) $\Rightarrow$ photon A ($m_A = 0$)

. weak (QFD) $\Rightarrow$ $\underbrace{W^+, W^-, Z}_{M_W \simeq M_Z \simeq 80 \text{ GeV}}$

$(m_p \simeq \text{GeV})$

- $c = 1 \Rightarrow \boxed{d[t] = d[L]}$

- $\hbar = 1 \Rightarrow \boxed{d[m] = d[L]^{-1}}$

$\uparrow$

$[p, q] = i$

$p = mv \Rightarrow d[p] = d[m]$

- strong $\Rightarrow$ 8 gluons $(m = 0)$

Neutrino history

$n \to p + e$ $\quad$ $\boxed{\beta \text{ decay}}$

$\Downarrow$

$E_e = m_n - m_p$

$$\boxed{{}^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni}}$$

Bohr : $\Delta E \neq 0$!?

Pauli : 1930

$$\mathrm{Co} \to \mathrm{Ni} + e + \underset{\substack{\uparrow \\ \text{neutron}}}{n}$$

Chadwick 1932 → neutron

Fermi 1934 – theory of β decay :

neutron → neutrino

$$n \to p + e + \bar{\nu}_e \quad (\Delta l \neq 0)$$

$$\left.\begin{aligned} e &= \text{lepton} \\ \nu &= \text{lepton} \end{aligned}\right\} \boxed{\begin{gathered}\text{Lepton \# } (L) \\ \text{is conserved}\end{gathered}}$$

Effective vs fundamental

- Effective

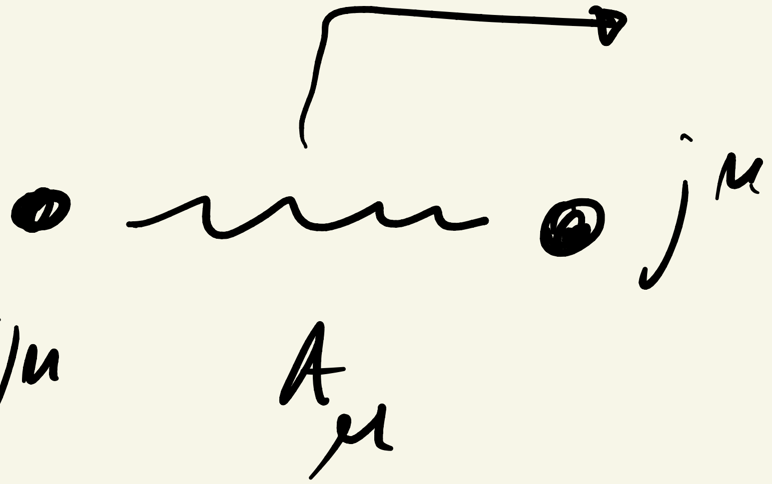
$$\boxed{\text{Newton}}$$

$$\boxed{V_{gr} = G_N \frac{m_1 m_2}{r}}$$

- Fundamental $\quad U(1)$ (QED)

$$\boxed{e\,\underset{\underset{\text{photon}}{\uparrow}}{A_\mu}\,j^\mu_{em}} : \quad \partial^\mu j_\mu^{em} = 0$$

$$\Big\Downarrow \text{ effective}$$



$$H_{eff} = \qquad j^\mu j_\mu$$

digression:

$$V_{q\bar{q}} \sim 1/r \longleftrightarrow ?$$

$\Downarrow$ go back

$$\mathcal{H}_{eff} = \frac{1}{q^2} \underbrace{j^{\mu}_{em} \, j_{\mu}^{em}}_{d=6} \qquad (d=4)$$

$d(\mathcal{H}) = d(\mathcal{L}) = ?$ in units of mass

$\hbar = 1 \Rightarrow d[s] = 0$

$$\Rightarrow \partial_\phi \left[\int d^4x \, \mathcal{L} \right] = 0$$

$$\Rightarrow \boxed{d(\mathcal{L}) = 4 \text{ in units of mass}}$$

$$\mathcal{L}_M(A) = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \qquad (d=4)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\Rightarrow \boxed{d(A) = 1}$$

$$\Uparrow$$

$$(\partial A)^2 \sim m^2 A^2$$

$$\mathcal{L}_{int} = e\, j^{\mu}_{em} A_{\mu} \qquad (d=4)$$

$$\Downarrow \qquad \longrightarrow \quad e \simeq 1/3$$

$$\boxed{d(j^{\mu}) = 3}$$

$$\Downarrow$$

$$\mathcal{H}^{em}_{eff} = \frac{1}{q^2}\, j^{\mu}_{em}\, j_{\mu}^{em} \qquad (em)$$

$$= 1/\mathrm{MeV}^2 \quad -''-$$

q = exchange momentum

$(q \simeq \mathrm{MeV})$

$\Downarrow$ Fermi

$$\mathcal{H}^{(w)}_{eff} = G_F\, j^{\mu}_{w}\, j^{w}_{\mu}$$

$$\Big\uparrow$$

$\mathrm{GeV} = 10^{3}\,\mathrm{MeV}$

$$G_F \simeq 10^{-5}\,\mathrm{GeV}^{-2}$$

$$\Downarrow$$

$$\boxed{\sigma(\nu) = ?}$$

$$d[\sigma] = -2$$

$$\Rightarrow \sigma(\nu) \cong G_F^{2}\, E^{2} \qquad (E \gtrsim m_e)$$

$$E = \mathrm{MeV} = 10^{-3}\,\mathrm{GeV}$$

$$\Rightarrow \sigma(\nu) \simeq 10^{-10}\, 10^{-6}\ \mathrm{GeV}^{-2}$$

$$\simeq 10^{-16}\ \mathrm{GeV}^{-2}$$

$$\mathrm{GeV}^{-1} = m_p^{-1} = \lambda_c(p)$$

$$\simeq 10^{-14}\ \mathrm{cm}$$

$$\Rightarrow \boxed{\sigma(\nu) \simeq 10^{-44}\ \mathrm{cm}^2}$$

<u>Compare</u>

$$\sigma(e) \simeq E^{-2} \simeq (\mathrm{MeV})^{-2}$$

$$\simeq 10^{+6}\ \mathrm{GeV}^{-2} \simeq 10^{-22}\ \mathrm{cm}^2$$

$$\boxed{1956 \quad \nu \text{ is discovered}}$$

Cowen, Reines

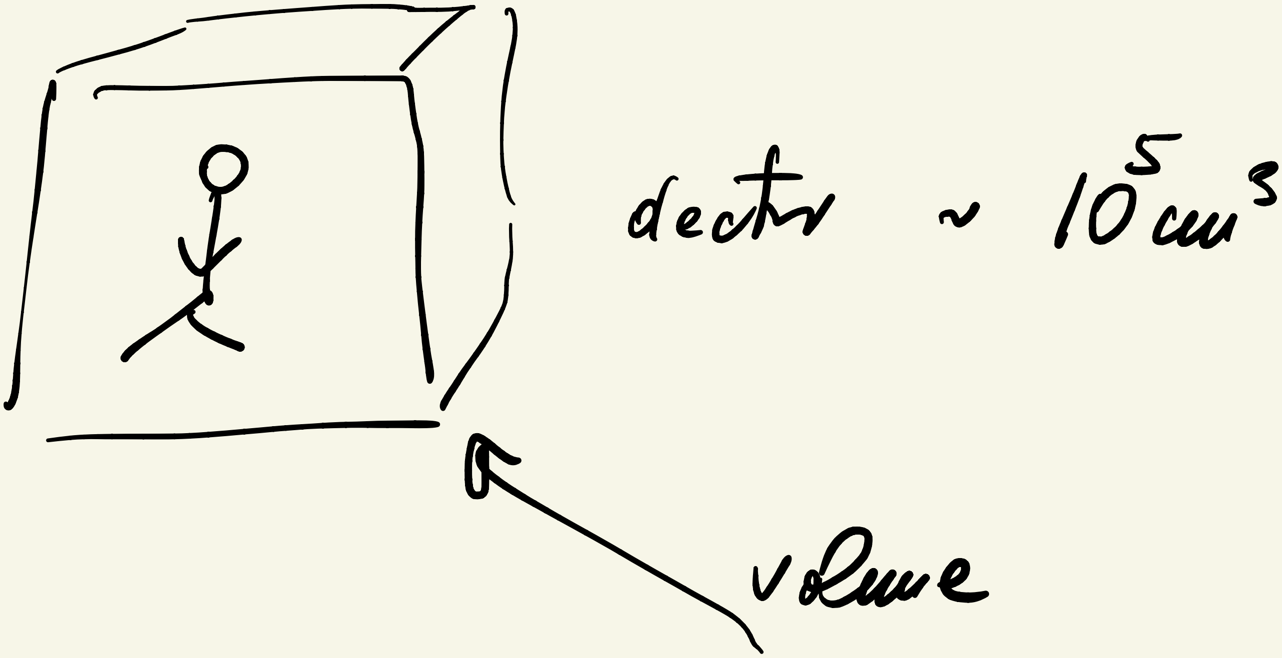
reactors (Pontecorvo)

$$\Phi = 10^{13}/\text{cm}^2\text{sec} \quad (\#\ \nu)$$

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

$$\boxed{\bar{\nu}_e + p \longrightarrow n + e^+}$$

water



$$\# = \Phi \cdot \sigma \cdot n \cdot V$$

$$= 10^{13}/\text{cm}^2\,\text{sec} \cdot 10^{-44}\,\text{cm}^3 \cdot 10^{24}/\text{cm}^3 \cdot 10^{5}\,\text{cm}^3$$

$$\simeq 10^{-2}/\text{sec} \simeq 1/\text{min}$$

$$\sim 30/\text{hr}$$

"Everything comes to him who

knows how to wait"

"free mean path" λ

$$\lambda_\nu = \frac{1}{\sigma \cdot n \cdot v} \simeq 10^{20}\,\mathrm{cm}$$

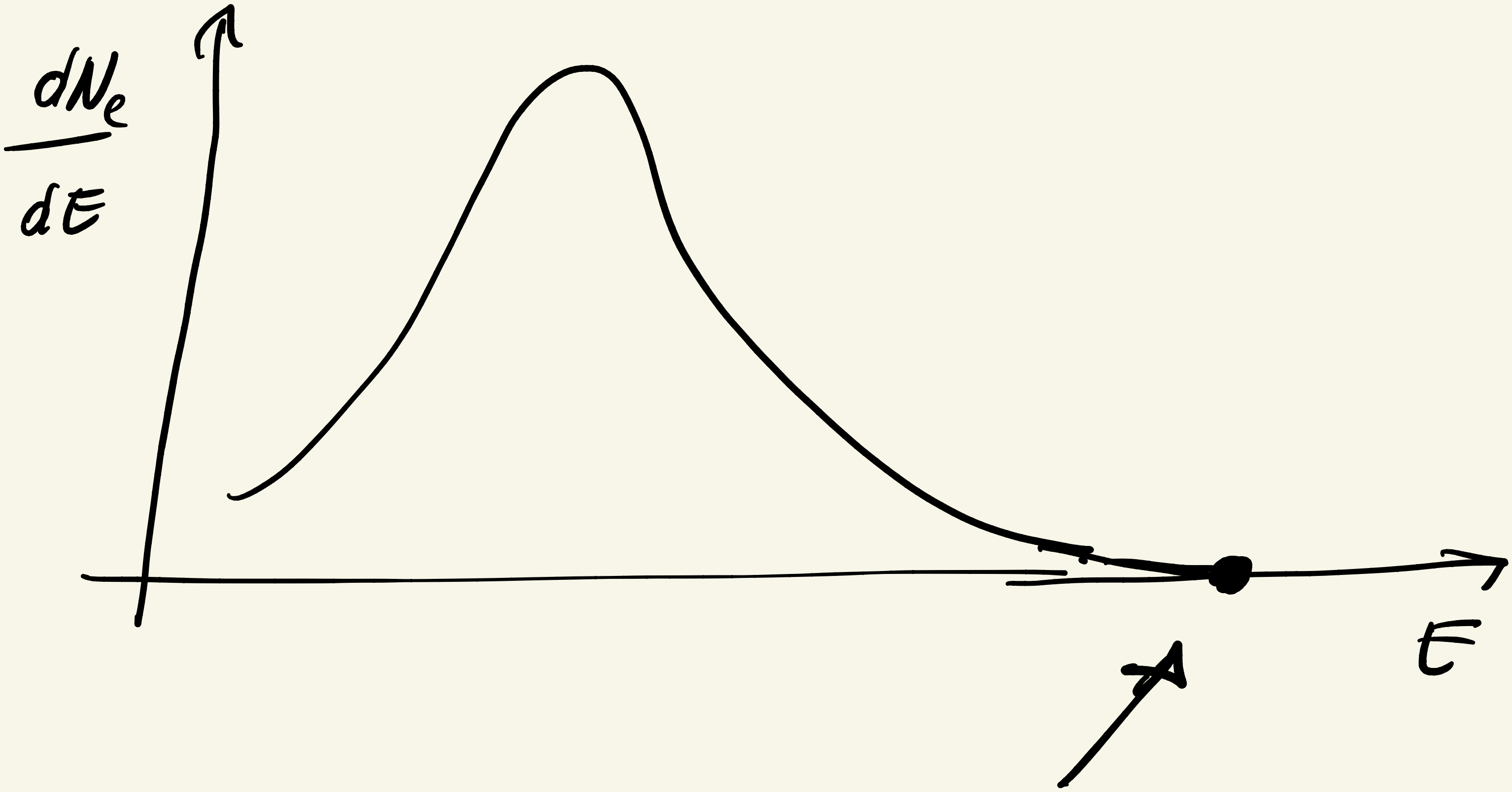
10^{-44} 10^{-24}

Neutrino mass

$$\boxed{m_\nu \leq eV}$$

(direct)

KATRIN



ν mass matters

$$\frac{dN_e}{dE} \propto E_e\, p_e\, E_\nu\, p_\nu$$

$$E_\nu = E_i - E_f - (E_e = m_e + \overset{\text{kinetic energy}}{\overset{\downarrow}{T}})$$

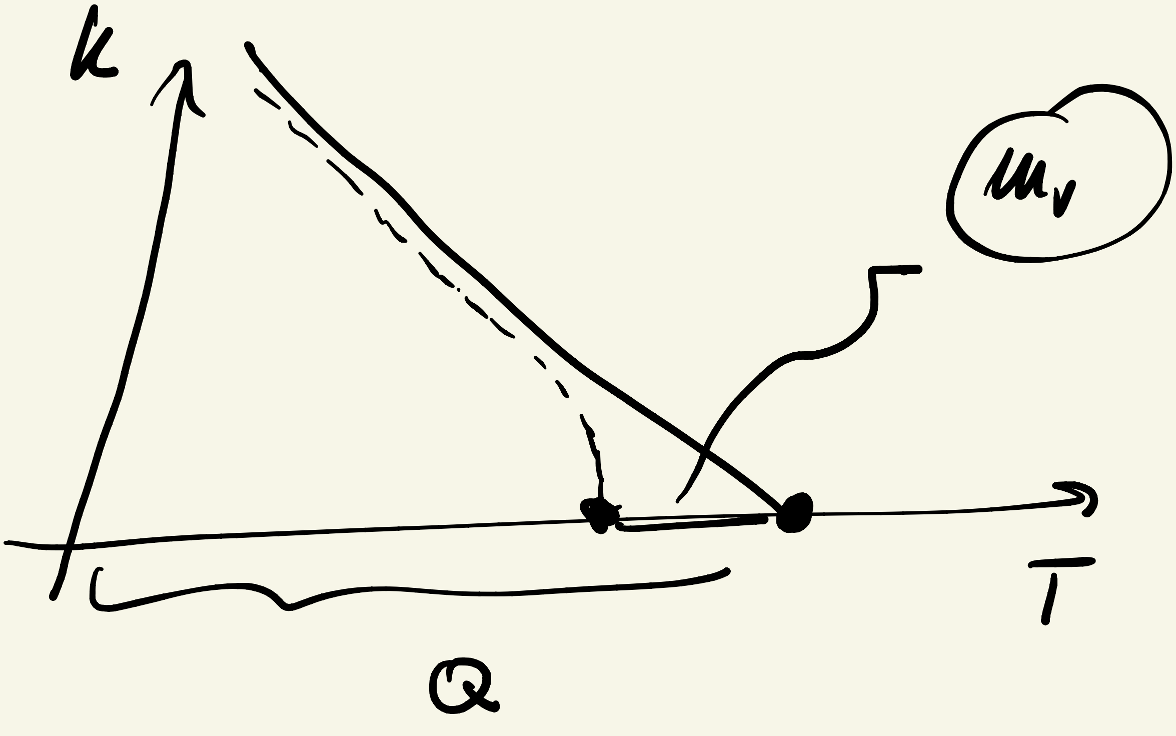
$$= \underbrace{E_i - E_f - m_e}_{Q} - T$$

$$(E_\nu = Q - T)$$

$$p_\nu = \sqrt{E_\nu^2 - m_\nu^2}$$

$$= \sqrt{(Q-T)^2 - m_\nu^2}$$

$$m_\nu = 0 \Rightarrow \sqrt{\frac{dN_e}{dE_e}} \propto (Q - T) = K$$



Tritium $H \rightarrow He + p + \bar{\nu}_e$

$Q \simeq 18 \text{ keV}$