Neutrino Physics Course

Lecture I

LMU

Spring 2022

Why neutrino?

- Essence of neutrino (mass) physics

  SM = Standard Model

  $SM \Rightarrow m_\nu = 0$

- $\exists$ mass $\to$ door to new physics (Beyond the SM = BSM)

- P violation = crux of it all

  fall and rise of parity

- Left-Right (LR) Symmetric Model = LR SM

LRSM: a (the?) theory of ν mass

$\Updownarrow$

SM: theory of charged fermions (+ W, Z) masses

$\Uparrow$

Higgs mechanism

Holy Grail: quest to grasp origin and nature of ν mass

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violation of lepton number

(LNV)

e = lepton
ν = –"–

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$\Delta L = 2$

- neutrino-less double beta decay

  $(0\nu 2\beta)$

$n + n \rightarrow p + p + e + e$

• KS process = analog at LHC

$$p + p(\bar{p}) \to e + e + \underbrace{j + j}_{\text{jets}}$$

CMS + ATLAS

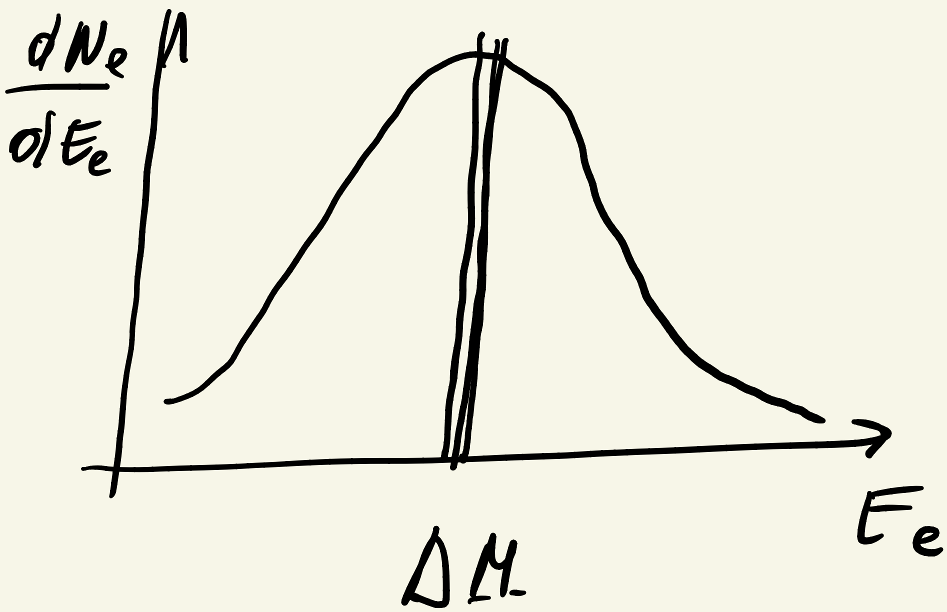
History of ν birth

Chadwick 1914 – 20's

β decay: $Co^{60}_{27} \to Ni^{60}_{28} + e$

$$\Delta M = E_e = \text{fixed}$$

$\Downarrow$



Bohr: $\Delta E \neq 0$

Pauli 1930 4/12

Postcard → Tubingen conf.

$\exists$ neutron $(Q = 0)$

1932 Chadwick ⇒ neutron

→ neutrino (= little

natro)

$m_\nu \le MeV$ early days

today: $\boxed{m_\nu \le eV}$

KATRIN

$$\boxed{m_\nu = 0 \quad ??}$$

EM:

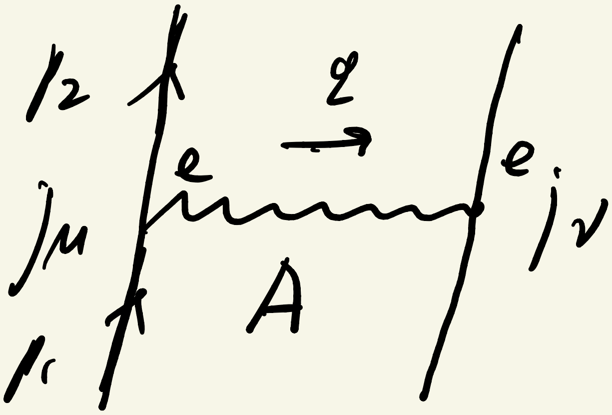
$$\boxed{e = 1/3}$$

$$e A_\mu j^\mu_{em} = \mathcal{L}_{int}$$

$$j^\mu_{em} = \bar\psi \gamma^\mu Q_{em} \psi$$

$$Q_{em} \psi = q_\psi \psi$$

e: $q_e = -1$ p: $q_p = +1$ n: $q_n = 0$



$$q \equiv p_1 - p_2$$

$$\frac{1}{q^2} g^{\mu\nu}$$

$$\Rightarrow \quad H_{eff}^{em} = j_\mu^{em} \Delta^{\mu\nu} j^\nu_{em}$$

$$\frac{1}{q^2} j^\mu_{em} j_\mu^{em}$$

Could I guess it?

Lorentz symmetry! $f(q^2)$

Exp: $m_A \leq 10^{-14}\, eV$

$A = \gamma$
$= $ photon

$$\Leftrightarrow \quad V_{em} \simeq \frac{1}{r} e^{-m_A r}$$

$$\simeq 1/r$$

SM: $m_A = 0$

1934 Fermi

$$j^\mu_w = \bar{p} \gamma^\mu n + \bar{\nu} \gamma^\mu e$$

$\Updownarrow$

$$n \longrightarrow p + \underbrace{e + \bar{\nu}_e}_{\Delta L = 0}$$

$$\mathcal{H}^F_{eff} \simeq \frac{1}{\Lambda_F^2} j^\mu_w \bar{j}^w_\mu \equiv \frac{G_F}{\sqrt{2}} j \bar{J}$$

$$\Leftrightarrow \mathcal{L}_{int} = g/\sqrt{2}\, j^\mu_w W^+_\mu + h.c.$$

$$\frac{G_F}{\sqrt{2}} = \frac{1}{\Lambda_F^2} \simeq 10^{-5} \text{GeV}^{-2}$$

$$\Lambda_F \simeq 300 \text{ GeV}$$

$$\boxed{Q \simeq \text{MeV}}$$

$$Q\,(\text{LHC}) \simeq 10^4 \text{ GeV} \leftarrow$$

<u>units</u> $c = \hbar = 1$

$d(t) = d(L)$ $\qquad [t] = [L]$

$\hbar = 1 \Leftrightarrow d(mvL) = 0$

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

$S = \int \mathcal{L} d^4x \qquad d(S) = [S] = 0$

$\Rightarrow d(\mathcal{L}) = d(L)^{-4}$

$= d(m)^4$

$d(\mathcal{L}) = 4$

units of mass

$$\mathcal{L}_D = i\,\bar{\psi}\gamma^\mu \partial_\mu \psi - m\,\bar{\psi}\psi$$

$$\bar{\psi} = \psi^\dagger \gamma^0$$

$$\Rightarrow \quad d(\psi) = 3/2 \quad \Rightarrow \quad d(j) = 3$$

$$\left(\begin{array}{c} \Downarrow \\ d(A) = 1 \end{array} \right)$$

$$\mathcal{H}_{eff}^{em} = f(q^2)\,\underbrace{j\,j}_{d=6}$$

$$\Downarrow$$

$$d\left(f(q^2)\right) = -2$$

$$\Rightarrow \quad f(q^2) = \frac{1}{q^2}$$

em: $1/q^2$ $q = \text{MeV}$

weak: $1/\Lambda_F^2$ $\Lambda_F \simeq 300\ \text{GeV}$

$$\frac{\sigma_W}{\sigma_{em}} \simeq \,?$$

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em: $\sigma_{em} \simeq \frac{e^2}{q^2}$

weak: $\sigma_W \simeq G_F^2\, q^2$ $(q > \text{MeV})$

$$H_{eff} \simeq G_F\, j_W\, j^W \qquad G_F \simeq \frac{1}{\Lambda_F^2}$$

$$\frac{\sigma_w}{\sigma_{em}} \simeq G_F^2 q^4$$

$$\simeq 10^{-10} \cdot 10^{-12} \simeq 10^{-22} \;!!$$

<u>Melfo, G.C.</u> Neutrino! ....

of about protagonist

- mean free path

$$\lambda_e \simeq \frac{1}{\sigma \cdot v \cdot n} \simeq 10^{-2}\,cm$$

cross section ↑ velocity ↑ density ↑

$$n \simeq 10^{24}/cm^3$$

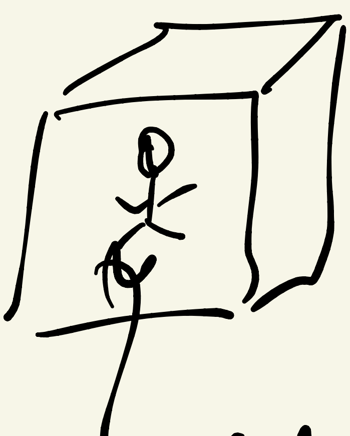
$$\boxed{\lambda_\nu \simeq 10^{20}\,\text{au}} \approx 10^{7}\, d_{SE}$$

sun-earth

Pontecorvo: reactors '40s

Cowan, Reines → '56

$\Phi = 10^{13}/\text{cm}^2\,\text{sec}$



water

detector

$V \simeq 10^5\, \text{cm}^3$

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

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

"good old days"

$$\#_{\text{events}} = \Phi \, \sigma_W \cdot n \, V$$

$$\sigma_W \simeq G_F^2 q^2 \simeq 10^{-10} \cdot 10^{-6} \, \text{GeV}^{-2}$$

$$\left(r_c(\text{proton}) \simeq 10^{-14} \, \text{cm} \quad (\pi) \right)$$

$$\simeq \frac{1}{m_p} \simeq \text{GeV}^{-1}$$

$$\boxed{m_p \simeq m_n \simeq \text{GeV}} \qquad (m_n > m_p)$$

$$\text{GeV}^{-2} \simeq 10^{-28} \, \text{cm}^2$$

$$\Rightarrow \boxed{\sigma_W \simeq 10^{-44} \, \text{cm}^2}$$

$$\# = 10^{13}\, 10^{-44}\, 10^{24}\, 10^{5} / \text{sec}$$

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

Pauli: "All comes to who knows how to wait"

<u>1956</u> Lee, Yang ($\not{P}$?)

June ⟶ December

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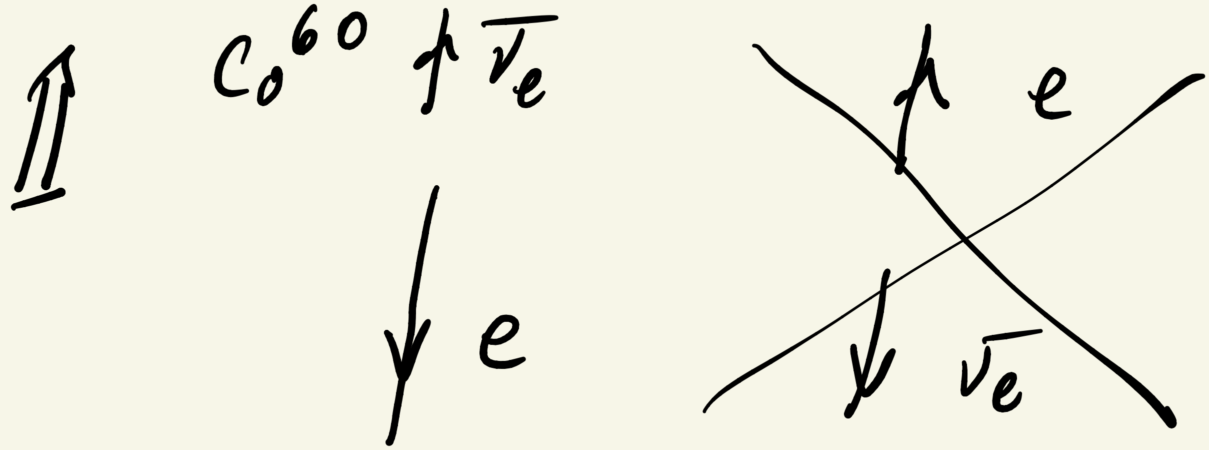
exp: Maximal $\not{P}$



<u>1957</u> Marshak, Sudarshan '57

$$j_w^\mu = \bar{p}\,\gamma^\mu \frac{1+\gamma_5}{2} u + \bar{\nu}\,\gamma^\mu \frac{1+\gamma_5}{2} e$$

$$= \bar{p}_L \gamma^\mu u_L + \bar{\nu}_L \gamma^\mu e_L$$

$\boxed{\gamma_5^2 = 1}$ ⇓

$$L \equiv \frac{1+\gamma_5}{2}, \quad R = \frac{1-\gamma_5}{2}$$

$L^2 = L, \quad R^2 = R, \quad LR = 0$

$\psi = L\psi + R\psi = \psi_L + \psi_R$

"V–A"

Weinberg 2009

"V–A was the key"

$\Downarrow$

1961 ⟶ 1967

Glashow   Weinberg, Salam

$\Downarrow$

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

of electro-weak unif

(ew)

⇓

the rest is history

SM : $m_\nu = 0$

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BSM

$$\{ \gamma_\mu, \gamma_\nu \} = 2 g_{\mu\nu} \qquad \mu = 0; 1, 2, 3$$

$$g_{\mu\nu} = \text{diag}\,(1, -1, -1, -1)$$

$$\{\gamma_5, \gamma_\mu\} = 0 \quad + \quad \gamma_5^2 = 1$$