Neutrino masses

In SM: $\lambda^e_{ij}\, \phi\, l_i\, \bar{e}_j$

↑ diagonalize using $U^l_L \times U^e_R$

No $\bar{\nu}$ $\Rightarrow$ $m_{\nu_i} = 0$.

$m_{\nu_i} \neq 0$: Experimental evidence for beyond SM

Recall SM has three "accidental" symms:

$$l_i \to e^{i\alpha_i} l_i$$
$$\bar{e}_i \to e^{-i\alpha_i} \bar{e}_i$$

e, μ, τ lepton #.

(anomalies violate ⇝ non pert. ...)

... interesting role...

E.g. if violate, mass w/out $\bar{\nu}$!

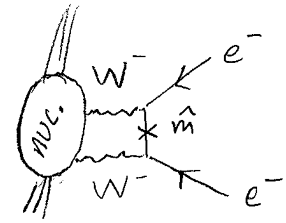
(unique feature – ν's changeless)

$$\mathcal{L}_{\hat{m}} = -\frac{\hat{m}_{ij}}{2} \nu_i \nu_j \quad (+\, h.c.)$$

↖ understood henceforth

recall violates $U(1)_{L_i}$

"Majorana mass," $\rightsquigarrow$ $(0\nu 2\beta)$



Also breaks $SU(2) \times U(1)$ – need source

e.g. in SM, $\tilde{\varphi} \cdot l_i$: singlet, $Y = 0$

$$\Rightarrow \quad \mathcal{L}_{\varphi^2 l^2} = -\frac{\hat{\lambda}_{ij}}{M} \tilde{\varphi} l_i \tilde{\varphi} l_j$$

... nonrenormalizable

or: can get from <u>higher rep of $SU(2)$ – 3!</u>

either way ... <u>new physics</u>

The old-fashioned way? $\bar{\nu}_i$ $\qquad Y=0$

$$m^{\nu}_{ij} \, l_i \bar{\nu}_j$$

e.g. SM

$$\lambda^{\nu}_{ij} \tilde{\Phi} l_i \bar{\nu}_j \quad , \quad m^{\nu}_{ij} = \lambda^{\nu}_{ij} \frac{v}{\sqrt{2}}$$

$\rightsquigarrow$ $U(1)_{L_i}$ conserved, $\bar{\nu}_i \to e^{-i\alpha_i} \bar{\nu}_i$

But, data: m_ν's $\lesssim .1\,\text{eV}$

$\Longleftrightarrow \quad \lambda^\nu_{ij} \lesssim 10^{-13} - 10^{-12}$

... begs explanation.

new symmetries involving $\bar{\nu}$?

$\bar{\nu}$ is different – pure singlet

This $\rightsquigarrow$ another new possibility:

$$\mathcal{L}_M = -\frac{M_{ij}}{2}\bar{\nu}_i\bar{\nu}_j \qquad \text{gauge allowed}$$

(but: spoils $U(1)_{L_i}$'s)

Most general possibility:

$$\begin{pmatrix}\nu \\ \bar{\nu}\end{pmatrix} \cdot \underbrace{\begin{pmatrix}\hat{m} & m^T \\ m & M\end{pmatrix}}_{\mathcal{M}} \begin{pmatrix}\nu \\ \bar{\nu}\end{pmatrix}$$

... and provides a candidate explanation for small masses!

Suppose $\hat{m} = 0$.

Mass estates : diagonalize $\mathcal{M}$.

M_{ij} in general is renormalized, might expect $M_{ij} \sim \Lambda_{NP}$. If $M \gg m$,

$$m_{light} \simeq -m\, M^{-1} m^T = \underline{\text{small}}$$

"Seesaw mechanism"

Effective field theory description:

$$\mathcal{L}_M = m_{ij}\, \nu_i \bar{\nu}_j + \frac{M_{ij}}{2} \bar{\nu}_i \bar{\nu}_j$$

$\uparrow$ symmetric

$\bar{\nu}$ heavy $\rightsquigarrow$ integrate out: $\delta / \delta \bar{\nu}_j$

$$0 = \nu^T m + \bar{\nu}^T M \qquad \text{(matrix notation)}$$

or

$$\bar{\nu}^T = -\nu^T m M^{-1}$$

$$\rightsquigarrow \mathcal{L}_{eff} = -\frac{\nu^T m M^{-1} m^T \nu}{2} \quad \checkmark$$

So: Maj. mass for ν $\left(\text{or } \frac{(\tilde{\phi} l)^2}{M} \right)$

$\updownarrow$

Effective description of theory w/ heavy $\bar{\nu}$

(either way, violate $U(1)_{L_i}$)

If so, what's M ?

$m \sim \lambda v$; suppose $\lambda \sim \mathcal{O}(1)$

(compare, e.g., top quark)

$m_\nu \lesssim .1\,eV \quad \Rightarrow \quad M \sim \frac{v^2}{1eV} \sim$ few $\times 10^{14}$ GeV.

a new heavy scale. just below M_{GUT} (... soon).

(note smaller λ doesn't get closer to M_{GUT})

Mixing (the evidence for m_ν's):

Weak current: $$J^{a\mu} = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}^{\dagger} \frac{\tau^a}{2} \bar{\sigma}^\mu \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}$$

~ CKM story:

1) Diagonalize m^e : U_L^ℓ, U_R^e

2) Then have $- \hat{m}_{ij} \nu_i \nu_j$

$\hat{m}_{ij}$ = symmetric complex = $U^\dagger m_i U^\dagger$ (↑ diag)

U "PMNS" Pontecorvo - Maki - Nakagawa - Sakata.

$\nu' = U_{PMNS}\, \nu$

weak e'states ↗ ↖ mass e'states.

CKM : 3 angles, 1 phase

PMNS : 3 angles, 3 phases (ex)

E.g parametrize as

$$U_{PMNS} = U_{23}(\theta_{23})\, U_{13}(\theta_{13}, \delta)\, U_{12}(\theta_{12}) \times \begin{pmatrix} 1 & & 0 \\ & e^{i\varphi_1} & \\ 0 & & e^{i\varphi_2} \end{pmatrix}$$

U_{23} ↑ rot in 2-3 plane

δ ↑ Dirac ~~CP~~ phase

↑ Majorana ~~CP~~ phases

Experiments

1) Sun : makes ν_e's.

we don't see enough. big puzzle for a long time.
(ν flux detection: Nobel '02, Davis / Koshiba)

θ_{12} + density effects $\rightsquigarrow$ $\nu_e \to \nu_\mu$ (↑ can now see.)

also reactor ν's : KamLAND

$\rightsquigarrow$ $\theta_{12} \simeq 33.9 \pm 1.6^\circ$ (big!)

also $\Delta m_{12}^2 \simeq (7.9 \pm .4) \times 10^{-5}\ eV^2$

2) Atmospheric   cosmic p's + atmosphere → π's.

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \searrow e^+ + \nu_e + \bar{\nu}_\mu$$

π^- : charge conjug.

$$\Rightarrow \quad R = \frac{N_{\nu_\mu}}{N_{\nu_e}} \sim 2. \qquad R_{obs} \sim .6$$

interp: $\nu_\mu \longrightarrow \nu_\tau$

+ K2K, MINOS, ... $\sin^2\theta_{23} \simeq .47$

i.e. $\theta_{23} \simeq \frac{\pi}{4}$ – maximal!

$$|\Delta m^2_{32}| \simeq (2.4 \pm .3) \times 10^{-3}\, eV^2$$

3) CHOOZ: $\sin^2\theta_{13} \lesssim 0.05$

etc.

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* All well-established data can be explained by mixing via U_{PMNS}

* Might consider other alternatives

  $\Gamma_Z \rightsquigarrow N_\nu = 3$; but sterile (singlet) can ⇝ large mixing

* Whatever new physics is, it ultimately needs to explain ν-masses.