

Probing the origin and nature of neutrino mass

Lecture IV

Fermilab



$d = 5$ effective interaction

and neutrino mass

We have seen that LRSM provides a self-contained, predictive theory of neutrino mass.

Summary of central features

$$\cdot G_{LR} = \underbrace{SU(2)_L \times SU(2)_R \times U(1)}_{LR} {}_{B-L}^g \bar{g}$$

$$\gamma_\mu \rightarrow D_\mu = \partial_\mu - ig T_a A_{\mu L}^a - ig T_a \overset{c}{A}_{\mu R}^a - i\bar{f}^\dagger \frac{B-L}{2} A_{\mu}^{BL}$$

• matter

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \xleftrightarrow{P} \begin{pmatrix} u \\ d \end{pmatrix}_R = q_R$$

$$l_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \xleftrightarrow{P} \begin{pmatrix} \nu \\ e \end{pmatrix}_R = l_R$$

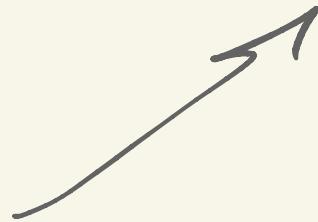


$$Q_{em} = \underbrace{T_{3L} + T_{3R}}_{LR \text{ sym.}} + \frac{B-L}{2} \quad (1)$$

Proof:

$$(B-L) Q_{LR} = \frac{1}{3} Q_L \quad (\text{show})$$

$$(B-L) l_{LR} = (-1) l_L \quad (-1 -)$$



use the knowledge

of $T_{3L}, T_{3R}, Q_{\text{em}}$

$$\bullet \quad G_{LR} \longrightarrow G_{SM}$$
$$\langle D_R \rangle = v_R$$

One chooses :

$\Delta_R = SU(2)_R$ triplet, $B-L=2$

$\Downarrow LR$

$\exists \Delta_L = SU(2)_L - 11-, -11-$

\Downarrow

$\mathcal{L}_Y(\Delta) = l_L^T C i\sigma_2 \Delta_L Y_\Delta l_L +$

$l_R^T C i\sigma_2 \Delta_R Y_\Delta l_R + h.c.$

Exercise: Show this is invariant

under G_{LR} . Use:

$$(2) \quad \begin{aligned} \Delta_L &\rightarrow U_L \Delta_L U_L^+ \\ V_R &\rightarrow V_R \Delta_R V_R^+ \end{aligned} \quad \left. \begin{array}{l} \text{adjoint} \\ \text{ver. =} \\ = \text{triplets} \end{array} \right\}$$

$$\Delta_{L,R} = \begin{pmatrix} \delta^+ & \delta^{++} \\ \delta_0 & -\delta^+ \end{pmatrix}_{L,R}$$

from (1) and (2), and

$$(B-L) \Delta_{L,R} = 2 \Delta_{L,R}$$

One shows: $\langle \Delta_L \rangle = 0, \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$

||

minimum in a pathim

of parameter space



$$M_{w_R} = g v_R$$

$$M_{z_R} = \sqrt{g^2 + \bar{g}^2} v_R$$

$$M_{\nu_R} = Y_D v_R$$

$$\bullet \quad N_C = C \bar{\nu}_R^\top$$

$$\mathcal{L}(v, N) = N_L^\top C M_\Delta v_L + \frac{1}{2} N_L^\top C M_N N_L$$
$$(M_N = M_{\nu_R}^*) \quad + h.c.$$

$$= \frac{1}{2} \left[N_L^T C M_D V_L + V_L^T C M_D^T N_L \right. \\ \left. + N_L^T C M_N N_L \right]$$



$$M_{VN} = \begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix} \begin{matrix} J_L \\ N_L \end{matrix}$$

$$V_L \quad N_L$$

$$M_N \gg M_D$$



$$\binom{v}{N}_L \rightarrow v \binom{v}{N}_L \therefore$$

$$U^T U = I = U U^+$$

$$U^T M_{VN} U = D_{VN} \quad (\text{diagonal})$$

$$\Rightarrow U = \begin{pmatrix} 1 & \theta^+ \\ -\theta & 1 \end{pmatrix}, \quad \theta \ll 1$$

$$\Downarrow \quad \left(\Theta = \frac{1}{M_N} M_D \right)$$

$$D_{VN} \underset{\approx}{=} \begin{pmatrix} M_V & 0 \\ 0 & M_N \end{pmatrix} \therefore$$

$$M_V = -M_D^T \frac{1}{M_N} M_D$$

see saw

• P: $M_D = M_D^+$

• C: $M_D = M_D^T$

(C)

$$\Rightarrow \underline{M}_v = - M_D \frac{1}{M_N} M_D$$



$$M_D = i M_N \sqrt{\frac{1}{M_N} \underline{M}_D}$$

(Lecture III)

$$\Rightarrow \boxed{\theta = i \sqrt{\frac{1}{M_N} \underline{M}_v}}$$

$$V_L \rightarrow V_L - N_L \theta^+$$



$$\bar{V}_L \gamma^\mu e_L W_\mu^+ \rightarrow \bar{V}_L \gamma^\mu e_L W_\mu^+$$

$$- \bar{N}_L \gamma^\mu \theta e_L W_\mu^+$$

$$\Rightarrow \bar{N}_L \gamma^\mu \theta e_L W_\mu^+ + \bar{e}_L \gamma^\mu \theta^+ N_L W_\mu^-$$



$$N \rightarrow e^+ W^+ (\theta^+) \quad \} \text{ true}$$

$$N \rightarrow \bar{e}^- W^- (\theta) \quad \} \quad N^c = N$$

N_{decays} predicted from

$$\Theta = i \sqrt{\frac{1}{M_N} M_V}$$

M_N : measure @ colliders

(LHC?)

M_V : $\rightarrow l^- l^+$ from oscillations, $0\nu\beta\beta$

• N produced via W_R (Lecture III)



(i) N_{decays} predicted

(ii) $N = \text{Mass} m_\nu \Leftrightarrow$

NJ process

$$N \rightarrow \begin{cases} e^+ w^+ & (50\%) \\ \bar{e}^- w^- & (50\%) \end{cases}$$



$$p + p \rightarrow e + e + j + j \quad (\text{lecture III})$$

SM: $m_f \rightarrow \Gamma(h \rightarrow f\bar{f}) \propto m_f^2$

LRSM: $M_V, M_N \rightarrow \Gamma(N \rightarrow e\bar{e}) \propto \theta^2$

$$\theta = i \sqrt{\frac{1}{M_N M_V}}$$

Giving up LR



Models of ν mass - provided
a protonini, custom-fit to give
observation. Different from LRSM!

ν = massive, seesaw, ... = all
predicted.

Example: seesaw

add $\nu_R(z)$



problems:

(i) how to produce N ?

$$(ii) M_0 = \sqrt{M_W} \quad 0 \quad \sqrt{M_1}$$

$$OO^T = 0$$

est. bay



generic problem of 'models'

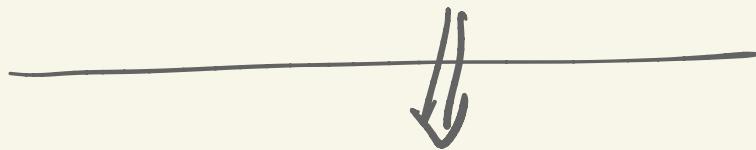
↓ instead, $d=5$

Wenley 1979

only SD particles!

$$l_L = \begin{pmatrix} v \\ e \end{pmatrix}_L, \quad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

e_R



$$(i) \underbrace{(l_L^T i\sigma_2 \phi)(\phi^T i\sigma_2 l)}_{\Delta_{\text{new}}} \overline{\Delta_{\text{new}}}$$

$$d=5$$

effective int. \longleftrightarrow entology

$$\frac{G_F}{\sqrt{2}} \bar{\psi}_\mu^W \bar{\psi}_w^a \quad \begin{pmatrix} \text{Fermi} \\ d=6 \end{pmatrix}$$

Take $\phi_m = \begin{pmatrix} v \\ v+h \end{pmatrix}$



$$\frac{v_L^T C v_L (v+h)^2}{\Lambda_{\text{new}}} =$$

$$= \frac{v_L^T C v_L}{\Lambda_{\text{new}}} (v^2 + 2vh + \dots)$$



$$m_v = v / \lambda_{new} \quad (M_w = \frac{q}{2} v)$$

$$\gamma_v = v / \lambda_{new} = \frac{m_v}{\varphi}$$



$$\gamma_v = \frac{q}{2} \frac{m_v}{M_w} \leftrightarrow \gamma_e = \frac{q}{2} \frac{m_e}{M_w}$$

$$\Gamma(h \rightarrow vv) \propto \gamma_v^2 \leq 10^{-22} !$$

negligible

Notice: if $N = \text{heavy} \Rightarrow$

$$\frac{v^2}{\lambda_{new}} = \frac{m_D^2}{m_N} = \frac{y_D^2 v^2}{m_D}$$

↓

$$\frac{1}{\lambda_{new}} = \frac{y_D^2}{m_N}$$

If we cannot produce N

\Rightarrow
 Of = 5 language of
 Weinbey is better

(iii) another $d=5$

$$\frac{(\ell^T i\sigma_2 \vec{\sigma} \phi) c (\phi^T i\sigma_2 \vec{\sigma} \ell)}{\Lambda_{\text{new}}}$$

(iv)

$$\frac{(\ell^T i\sigma_2 \vec{\sigma} c \ell) (\phi^T i\sigma_2 \vec{\sigma} \phi)}{\Lambda_{\text{new}}}$$

Λ_{new}



Show (exercise 3) that

$$(i) \propto (i') \propto (iv)$$

- Show:

$$(\ell^T i \sigma_2 c \ell) (\phi^T i \sigma_2 \phi) = 0$$



There are only 3 different types of $d=5$ $\Delta L=2$ interaction

— and they give one and the same final result (up to a constant)

Analysis

(i) The first operator is based
on

$$l^T i \sigma_2 \phi$$


$SU(2)_L$ singlet, $\gamma = 0$.

fermion under Lorentz



This $d=5$ operator corresponds
to the exchange of singlet SM

fermion = RH neutrino ν_R

↓

This corresponds to the
review discussed in the
lectures = usually coined as
Type I review.

(ii) the 2nd operator is based
on

$$l^T i \sigma_2 \rightarrow \phi$$

SU(2) triplet (prove it!),

$\gamma = 0$, fermion



corresponds to the exchange
of triplet fermion - analog
of RH neutrino. This is
called type III seesaw.

(iii) The 3rd operator is due

to the exchange of

$$l^\dagger i \sigma_2 \bar{\sigma}^* l$$


$SU(2)$ triplet, $\gamma = -2$, scalar



Corresponds to the exchange
of $SU(2)$ scalar triplet ($\gamma = -?$)
- called type II seesaw.



if these fields are too heavy
to be produced \rightarrow they lead
to the same physics described
by the effective $d=5$ interaction.

In other words, unless we produce
these states, $d=5$ language is
actually more appropriate.