

# Neutrino Physics

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## Lecture XI

2/6/2023

LMU

Summer 2023

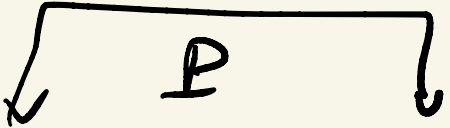
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# LR theory: Higgs sector

LR symmetric Model = LRSM

•  $G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$



•  $l_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_R = l_R$

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

(Note: The  $\nu$  in the right-hand side is circled in red in the original image.)

• Higgs

$$\phi_{LM} \in \Phi$$

$$\phi_{SM} \rightarrow U_L \phi_{SM}$$

$$\Phi \rightarrow U_L \Phi U_R^+$$

bi-doublet

$$\mathcal{L}_Y = \bar{\ell}_L \gamma_2 \Phi \ell_R + h.c.$$

$$+ \bar{l}_L \gamma_e \Phi l_R + \dots$$

$$\ell_L \rightarrow U_L \ell_L$$

$$\ell_R \rightarrow U_R \ell_R$$

$$l_L \rightarrow \dots l_L$$

$$l_R \rightarrow U_R l_R$$



$$\underline{\Phi} = \underbrace{\begin{pmatrix} \tilde{\phi}_1 \\ \phi_2 \end{pmatrix}}_{\text{SM doublets}}$$

$$\phi \equiv \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

$$\tilde{\phi} \equiv i\sigma_2 \phi^* \equiv \begin{pmatrix} \varphi_0^{*-} \\ -\varphi^- \end{pmatrix}$$

$$(\phi, \tilde{\phi}) \rightarrow U_L(\phi, \tilde{\phi})$$

$$\underline{\Phi} = \begin{pmatrix} \phi_1^{0*-} & \phi_2^+ \\ -\phi_1^- & \phi_2^0 \end{pmatrix}$$

$$\mathcal{L}_Y = (\bar{u}_L \quad \bar{d}_L) \begin{pmatrix} \phi_1^{0*} & \phi_2^+ \\ -\phi_1^- & \phi_2^0 \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$= \bar{u}_L \phi_1^{0*} u_R + \bar{u}_L \phi_2^+ d_R + \\ - \bar{d}_L \phi_1^- u_R + \bar{d}_L \phi_2^0 d_R$$

Is this all?

Reminder  $\widehat{SM}$

$$\mathcal{L}_Y^{SM} = \bar{e}_L \gamma_d \phi d_R + \bar{e}_L \gamma_u \tilde{\phi} u_R \\ \uparrow \quad \quad \quad + h.c.$$

$$i\int \bar{\psi} \psi \Rightarrow \int \bar{\psi} \propto \psi^*$$

LR

$$\begin{aligned} i\int \bar{\psi} \psi &\Rightarrow \int \bar{\psi} = i\sigma_2 \bar{\psi}^* (-i\sigma_2) \\ &= \sigma_2 \bar{\psi}^* \sigma_2 \\ &\propto \bar{\psi}^* \end{aligned}$$

$\Downarrow$  important

$$\mathcal{L}_Y^{(LR)} = \bar{q}_L (Y_q \bar{\Phi} + \tilde{Y}_q \tilde{\Phi}) q_R + \bar{l}_L (Y_e \bar{\Phi} + \tilde{Y}_e \tilde{\Phi}) l_R + h.c.$$

↕ endology with SM

$$Y_q, \tilde{Y}_q \leftrightarrow Y_u, Y_d$$

LR SM = equally predictive  
as SM

$$G_{LR} \longrightarrow G_{SM} \longrightarrow U(1)_{em}$$

$$M_R = \langle \text{new Higgs} \rangle \quad \langle \Phi \rangle \cong M_W$$
$$= M_{new}$$

SM:

$$M_W^2 = \left(\frac{g}{2}\right)^2 \langle \phi \rangle^2$$

$$M_Z^2 = \frac{g^2 + g'^2}{4} \langle \phi \rangle^2 = \frac{M_W^2}{\cos^2 \theta_W}$$

LR:  $\phi_1, \phi_2 \quad (i=1,2)$

$$\mathcal{L}_\Phi = \frac{1}{2} (D_\mu \phi_i)^\dagger (D^\mu \phi_i) + \dots$$





$$M_W^2 = \frac{g^2}{4} \left[ \langle \phi_1 \rangle^2 + \langle \phi_2 \rangle^2 \right]$$

$$M_Z^2 = \frac{g^2 + g'^2}{4} \left[ \dots \right] = \frac{M_W^2}{\cos^2 \theta_W}$$

$$\boxed{\mu^2 = \lambda v^2}$$

SM

$$V = \frac{\lambda}{4} (\phi^\dagger \phi - v^2)^2$$

$$= -\frac{\mu^2}{2} \phi^\dagger \phi + \frac{\lambda}{4} (\phi^\dagger \phi)^2 + \text{const.}$$

LR

$$V = -\frac{\mu^2}{2} \text{Tr} \bar{\Phi}^\dagger \Phi + \dots$$

$$\left| \bar{\Phi} \rightarrow U_L \bar{\Phi} U_R^\dagger \right.$$

$$\Phi^+ \rightarrow U_R \Phi^+ U_L^+$$



$$\Phi^+ \Phi \rightarrow U_R \Phi^+ \Phi U_R^+$$

$$= -\frac{\mu^2}{2} (\phi_1^+ \phi_1 + \phi_2^+ \phi_2) + \dots$$



$$\langle \phi_1^0 \rangle = v_1, \quad \langle \phi_2^0 \rangle = v_2$$

$$v^2 = v_1^2 + v_2^2 = v_{SM}^2$$



$$M_W^2 = \frac{g^2}{4} v^2 = M_Z^2 \cos^2 \theta_W$$

True for any # of  
SM doublets (Higgs)

$$M_W = \frac{g}{2} v \quad v = \sqrt{v_1^2 + v_2^2}$$

⇓

$$v_i \leq v = \frac{2}{g} M_W$$

$$\text{heavy} = m_h \propto M_{\text{new}} = M_R$$

$$\text{light} = m_e \ll M_W$$

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Exp. (LHC)



$$M_R \gg M_W = 80 \text{ GeV}$$

$$(M_R > 4 \text{ TeV})$$

# New Higgs?

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

↓ (new Higgs)

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

$$Q_{em} = T_{3L} + \underbrace{\frac{Y}{2}}_{= T_{3R} + \frac{B-L}{2}}$$





Melipatos, Patu '74

$$(\Delta_L, \Delta_R \in \mathbb{R})$$

$\Downarrow$

$$V = -\frac{\mu^2}{2} (\Delta_L^2 + \Delta_R^2)$$

$$+ \frac{\lambda}{4} (\Delta_L^4 + \Delta_R^4)$$

$$+ \frac{\lambda'}{2} \Delta_L^2 \Delta_R^2$$

$$= -\frac{\mu^2}{2} (\Delta_L^2 + \Delta_R^2) + \frac{\lambda}{4} (\Delta_L^2 + \Delta_R^2)^2$$
$$+ \left( \frac{\lambda' - \lambda}{2} \right) \Delta_L^2 \Delta_R^2$$

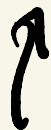
•  $\lambda' = \lambda$  (not physical)

$$\boxed{\mu^2 > 0}$$

Hint:  $\ominus \mu^2 \Rightarrow$  SSB



$$\Delta^2 \equiv \Delta_L^2 + \Delta_R^2 \Rightarrow \langle \Delta \rangle^2 = \mu^2 / \lambda$$



not clear who gets a vev

$$\bullet \lambda' - \lambda > 0$$

$$(\lambda' - \lambda) \Delta_L^2 \Delta_R^2 \geq 0$$

$$\text{min} \rightarrow \begin{cases} \langle \Delta_L \rangle = 0 \\ \langle \Delta_R \rangle \neq 0 \end{cases}$$

$$\bullet \lambda' - \lambda < 0$$

$$(\lambda' - \lambda) \Delta_L^2 \Delta_R^2 \leq 0$$

$$\Downarrow \begin{cases} \langle \Delta_L \rangle \neq 0 \neq \langle \Delta_R \rangle \end{cases}$$



$$\langle \Delta_L \rangle = \langle \Delta_R \rangle$$

$$\frac{\partial^2 V}{\partial \Delta_L^2} \Big|_{\langle \Delta_L \rangle = 0} = -\mu^2 \leftarrow \text{maximum}$$



$$\langle \Delta_L \rangle = 0, \langle \Delta_R \rangle = 0$$

is a maximum

NOT physical



$$\lambda' - \lambda > 0$$

we live  
here

minimum of  $V$

$$\langle \Delta_L \rangle = 0, \quad \langle \Delta_R \rangle = V_R$$

$\therefore$  ~~not~~ spurt.

$$(\lambda' - \lambda) \langle \Delta_L^2 \rangle \langle \Delta_R^2 \rangle = 0$$

minimizes  $V$

$\Downarrow$   
all  $m^2 > 0 \Leftrightarrow$  minimum

at the  $\langle O_L \rangle = 0, \langle O_R \rangle \neq 0$

Prove

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Reminder

$$V_{SM} = \frac{\lambda}{4} (\phi^\dagger \phi - v^2)^2$$

$\lambda > 0, \ominus$

we live here

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We established  $P$  :

$$0 = \langle \Delta_L \rangle, \quad \langle \Delta_R \rangle = \underline{M}_R$$

but

Mahepatra,  
September '75

who are these guys?

doublets?

triplets?

• original choice

$$\begin{array}{c} \Delta_L \quad \longleftrightarrow \quad \Delta_R \\ \underbrace{\hspace{10em}} \\ \text{doublets, } B-L = 1 \\ \underbrace{\hspace{10em}} \end{array}$$

↑

no coupling to  $f$

~~$\bar{f}_L \Delta_L f_R$        $\bar{f}_L \Delta_R f_R$~~

~~$\bar{f}_L \Delta_L f_L$~~       - - - -

" $s$ " =  $\frac{1}{2}$  ↓ ↙ ↘ ↓

" $s$ " =  $\frac{1}{2}, \frac{3}{2} \neq 0$

⇓

only  $\bar{f} \rightarrow f$

$$\left( \begin{array}{c} \nu \\ e \end{array} \right)_L \longleftrightarrow \left( \begin{array}{c} \nu \\ e \end{array} \right)_R$$



$$m_\nu \neq 0$$

but:  $m_\nu \leq 10^{-9} m_\tau !$

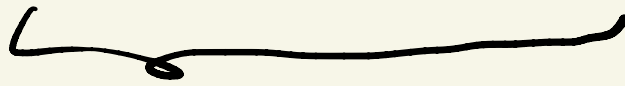


why? How?

- However,  $\nu_R$  could be Majorana ???

SM

$$J_R^T C J_R$$



$SU(2)_L$  inv. ;  $U(1)$  inv.

$Q_{em} = T_{3L} + \frac{Y}{2}$

$T_{3L} J_R = 0 \Rightarrow Y J_R = 0$

$Q_{em} J_R = 0$



LR

$M_{J_R} \propto M_R$



SM at "low" ( $E \ll M_R$ ) E

# Visible universe

stars (a, d, e)  $\rightarrow 10^{80}$

photons  $\rightarrow 10^{90}$

new turns  $10^{90}$

?????

$\mu_y \mu_B < \mu_x ?$

guesses  $\left\{ \begin{array}{l} \text{baryo} \\ \text{lepto} \end{array} \right.$



(5M)

$h \rightarrow \gamma\gamma$

discovery

4/7/2012

$h \rightarrow \gamma Z$

$\uparrow$

$\rightsquigarrow$

(3 $\sigma$ )

excess?

discovery : 5 $\sigma$