Neutrino Physics

Lecture XVIII

LMU

Summer 2021

Neutrino Physics Course

Lecture $\overline{\underline{\text{XVIII}}}$

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LR symmetry

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

$$SU(2)_L \xleftrightarrow{P\ (C)} SU(2)_R$$

- (q, ℓ)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \longleftrightarrow \begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

- Higgs (SSB)

$$\downarrow$$

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

$$M_{W_R} \simeq M_R \qquad\qquad M_L \simeq M_{W_L}$$

$$\frac{Y}{2} = T_{3R} + \frac{B-L}{2} \quad \Longleftrightarrow \quad \boxed{Q_{em} = T_{3L} + \frac{Y}{2}}$$

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

$$\Big\downarrow M_R$$

$$U(1)_Y$$

- at $M_L \simeq M_W \equiv M_{W_L}$

Higgs $= \phi$ (SM doublet)

$$\Downarrow$$

$$\Phi = \begin{pmatrix} \tilde{\phi}_1 & \phi_2 \end{pmatrix}$$

$$\mathcal{L}_Y = \bar{f}_L \, Y_\Phi \, \Phi \, f_R + h.c.$$
$$+ \bar{f}_L \, Y_{\tilde{\Phi}} \, \tilde{\Phi} \, f_R + h.c.$$

Q. What Higgs $\longrightarrow M_R$?

A?? Must be a doublet of $SU(2)_R$?

($\Leftrightarrow$ SM sym. breaking)

SM: ϕ $\therefore$ $\phi_0 = \begin{pmatrix} 0 \\ v \end{pmatrix}$

$\Downarrow$

$$\underbrace{\left(T_{3L} + Y/2\right)}_{Q_{em}} \phi_0 = 0$$

NOT true.

Any Higgs that leaves $\frac{Y}{2}$ is equally good!

$$\Updownarrow$$

any Higgs in SM that leaves Q_{em} is equally good

$$\boxed{\text{Glashow} \quad 1961}$$

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

$$\downarrow$$

$$U(1)_{em}$$

$\Rightarrow \quad \exists\, A \leftrightarrow$ coupled to Q_{em}

$$\Downarrow$$

$\exists\, Z$ with the current

$$J_\mu^Z = \bar{f}\left(T_3 - Q_{em} \sin^2\theta_W\right) f$$

$$\Downarrow$$

$\boxed{\text{whatever}}$ Higgs ϕ $\therefore$

$\boxed{\text{if}}$ $\boxed{Q_{em}\ \phi_0 = 0}$ (unbroken)

$$\Downarrow \qquad Q_{em} \equiv T_3 + Y/2$$

$$\boxed{\begin{aligned} A_\mu &= \sin\theta_W\, A_\mu^3 + \cos\theta_W\, B_\mu \\ Z_\mu &= +\cos\theta_W\, A_\mu^3 - \sin\theta_W\, B_\mu \end{aligned}}$$

- $D_\mu \phi = \left(\partial_\mu - ig\, T_a A_\mu^a - ig' \frac{Y}{2} B_\mu\right)\phi$

$$\Downarrow$$

$$D_\mu \phi_0 = \cdots\left(-ig\, T_3 A_\mu^3 - ig' \frac{Y}{2} B_\mu\right)\phi_0$$

$$A_\mu^3 \propto \frac{1}{g} A_\mu, \quad B_\mu \propto \frac{1}{g'} A_\mu$$

A_μ = massless photon

$$\Rightarrow D_\mu \phi_0 \propto -i\left(T_3 \frac{\cancel{g}}{\cancel{g}} A_\mu + \frac{Y}{2}\frac{\cancel{g'}}{\cancel{g'}} A_\mu\right)\phi_0$$

$$+ \cdots$$

$$\cancel{\propto} -i \underbrace{\left(T_3 + \frac{Y}{2}\right)}_{Q_{em}} A_\mu \phi_0 = 0$$

$$\Downarrow$$

$$\boxed{m_A = 0}$$

$$A_\mu^3 = \frac{c}{g}, \quad B_\mu = \frac{c}{g'}$$

$$\therefore \quad \frac{c^2}{g^2} + c^2/g'^2 = 1$$

$$\Rightarrow \quad c = \frac{g g'}{\sqrt{g^2+g'^2}}$$

- <u>neutral currents</u> $\swarrow$ $D_\mu = \ldots$

$$\bar{f} \gamma^\mu \left(g T_3 A_\mu^3 + g' \frac{Y}{2} B_\mu \right) f$$

$$= \bar{f} \gamma^\mu \left(T_3 \cancel{\frac{c}{g} g} + \frac{Y}{2} \cancel{\frac{c}{g'} g'} \right) A_\mu f$$

$$= \bar{f} \gamma^\mu \left(T_3 + \frac{Y}{2} \right) f \, A_\mu \times c$$

$$\equiv \bar{f} \gamma^\mu Q_{em} A_\mu \times e \implies \boxed{c = e}$$

$$\Downarrow$$

$$e = \frac{g g'}{\sqrt{g^2 + g'^2}} = g \sin\theta_W$$

$$= g' \cos\theta_W$$

$$\tan\theta_W = g'/g$$

$$A_\mu^3 = \sin\theta_W A_\mu + \cdots$$

$$B_\mu = \cos\theta_W A_\mu + \cdots$$

$$\Downarrow$$

$$\boxed{A_\mu = \sin\theta_W A_\mu^3 + \cos\theta_W A_\mu}$$

$$\Downarrow$$

but $Z \perp A \Rightarrow$

$M_Z = ?$

$$\boxed{Z_\mu = \cos\theta_w \, A_\mu^3 - \sin\theta_w \, B_\mu}$$

$\boxed{\text{Q. E. D.}}$

$$e = \frac{g g'}{\sqrt{g^2 + g'^2}}$$

$$\Leftrightarrow \quad \frac{1}{e^2} = \frac{1}{g^2} + \frac{1}{g'^2}$$

$$\Downarrow$$

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

any Higgs Δ_R will do,

$$\boxed{\text{ai long } \frac{Y}{2}\ \Delta_R^0 = 0}$$

$$\Updownarrow$$

$$\boxed{Q_{em}\ \phi_0 = 0 \text{ in SM}}$$

$$\Downarrow$$

Gauge boson spectrum in LR theory

SM: $Q_{em}\ \phi_0 = 0 \Rightarrow$

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \sin\theta_W & \cos\theta_W \\ \cos\theta_W & -\sin\theta_W \end{pmatrix} \begin{pmatrix} A_3 \\ B \end{pmatrix}_\mu$$

$$\tan\theta_W = g'/g$$

LR: $\quad v/2\, \Delta_0^R = 0 \Rightarrow$

$$\begin{pmatrix} B_\mu \\ Z'_\mu \end{pmatrix} = \begin{pmatrix} \sin\theta_R & \cos\theta_R \\ \cos\theta_R & -\sin\theta_R \end{pmatrix} \begin{pmatrix} A_{3R} \\ \bar{B}_\mu \end{pmatrix}$$

$$D_\mu^{LR} = \partial_\mu - ig\left(A_{3L}\, T_{3L} + A_{3R}\, T_{3R}\right)_\mu$$

$$- i\bar{g}\, \bar{B}_\mu\, \frac{B-L}{2} + \cdots$$

$$\left[\begin{array}{c} \tan\theta_R = \bar{g}/g \\ (g_L = g_R \equiv g) \end{array}\right]$$

$$\Downarrow$$

$$\frac{1}{g'^2} = \frac{1}{g^2} + \frac{1}{\bar{g}^2}$$ (analogy with SM)

$$g' = \frac{g\bar{g}}{\sqrt{g^2+\bar{g}^2}}$$

$$\tan\theta_W = \frac{g'}{g} = \frac{\bar{g}}{\sqrt{g^2+\bar{g}^2}}$$

$$\left(\tan\theta_R = \bar{g}/g \right)$$

$$\Rightarrow \boxed{\tan\theta_W = \sin\theta_R}$$

$$\boxed{\theta_W \simeq 30^\circ}$$

$$B_\mu = \sin\theta_R \, A^R_{\mu 3} + \cos\theta_R \, \bar{B}_\mu$$

$$Z'_\mu = \cos\theta_R \, A^R_{\mu 3} - \sin\theta_R \, \bar{B}_\mu$$

$$B_\mu = \tan\theta_W A^R_{\mu 3} + \sqrt{1-\tan^2\theta_W}\,\bar{B}_\mu \quad (*)$$

$$\boxed{Z'_\mu = \sqrt{1-\tan^2\theta_W}\, A^R_{\mu 3} - \tan\theta_W \bar{B}_\mu}$$

new (heavy) neutral gauge boson

$$\boxed{Z' \equiv Z_R}$$

$$\left.\begin{aligned} A_\mu &= \sin\theta_W A^L_{\mu 3} + \cos\theta_W B_\mu \\ Z_\mu &= \cos\theta_W A^L_{\mu 3} - \sin\theta_W B_\mu \end{aligned}\right\} \quad (\pounds)$$

$$\left.\begin{array}{l} \bullet\ Z \longleftrightarrow Z' \quad \text{in LR} \\ \\ \bullet\ A \longleftrightarrow Z \quad \text{in SM} \end{array}\right\}$$

$$J_\mu^A \neq J_\mu^Z$$

$$m_A \neq m_Z$$

$$\Downarrow$$

$$J_\mu^Z \neq J_\mu^{Z'}$$

$$m_Z \neq m_{Z'}$$

$$\boxed{m_{Z'} \gtrsim \text{TeV}}$$

(LHC)

- example of "funny" world:

$SU(2)_{L+R} \times U(1)_Y$: $\boxed{\rho \text{ good}}$

$\Rightarrow$ Adjoint Higgs $\Rightarrow$

$$\boxed{M_Z = 0, \quad M_W \neq 0}$$

How to probe the Higgs?

<u>SM;</u> any Higgs $\therefore$ $Q_{em}\,\phi_0 = 0$

but; $M_Z / M_W \leftarrow$ depends on Higgs e.g. $M_Z \cos\theta_W = M_W$

ϕ = SM doublet

$$\rho \equiv \frac{M_Z^2 \cos^2\theta_W}{M_W^2} = 1$$

<u>SM</u>: fermions chose <u>doublet</u>

<u>but</u> B S M (say LR)

Issue profound ?

$\Downarrow$

complete LR spectrum

$$A_\mu = \sin\theta_W A_{\mu 3}^L + \cos\theta_W \tan\theta_W A_{\mu 3}^R$$

$$+ \cos\theta_W \sqrt{1-\tan^2\theta_W}\, \bar{B}_\mu$$

$$\Downarrow \qquad (\cos 2\theta_W = \cos^2\theta_W - \sin^2\theta_W)$$

$$\boxed{A_\mu = \sin\theta_W (A_{\mu 3}^L + A_{\mu 3}^R) + \sqrt{\cos 2\theta_W}\, \bar{B}_\mu}$$

$$\boxed{\Leftrightarrow \quad Q_{em} = T_{3L} + T_{3R} + \frac{B-L}{2}}$$

$$\text{"}A_\mu \cdot A^\mu\text{"} = \sin^2\theta_W (1+1) + \cos^2\theta_W - \sin^2\theta_W$$

$$= \sin^2\theta_W + \cos^2\theta_W = 1$$

$$Z_\mu = \cos\theta_W\, A^L_{\mu 3} - \sin\theta_W \tan\theta_W\, A^R_{\mu 3}$$

$$- \sin\theta_W \sqrt{1-\tan^2\theta_W}\, \bar{B}_\mu$$

$$\boxed{Z_\mu = \cos\theta_W \left(A^L_{\mu 3} - \underline{\underline{\tan^2\theta_W}}\, A^R_{\mu 3}\right) - \tan\theta_W \sqrt{\cos 2\theta_W}\, \bar{B}_\mu}$$

$$\boxed{M_Z \cos\theta_W = M_W}$$

$\Uparrow$

bi-doublet

$M_{Z'} / M_{W'}$

$$\boxed{\begin{aligned} W &\equiv W_L \\ W' &\equiv W_R \end{aligned}}$$

$$J_\mu^{\ A} \equiv \bar{f}\, \gamma_\mu\, Q_{em}\, f \qquad (e\, A_\mu\, J^\mu_A)$$

$$J_\mu^{\ Z} = \bar{f}\, \gamma^\mu\, (T_{3L} - Q_{em} \sin^2\theta_W)\, f$$

$$\left(\frac{g}{\cos\theta_W}\, Z_\mu\, J^\mu_Z\right)$$

$$J_\mu^{\ Z'} = \bar{f}\, \gamma^\mu\, (?T_{3R} \pm Q \cdots)\, f$$

??? $\boxed{\text{to be completed}}$

$$\rho' \equiv M_{Z'}/M_{W'} \equiv M_{Z_R}/M_{W_R}$$

depends on choice of Δ_R

but $\rho' = ?$ (exp)

$$\Delta_R \xleftrightarrow{LR} \Delta_L$$

$$T_a^R \Delta_R \neq 0$$

$$\boxed{T_a^L \Delta_R = 0}$$ must

$$(\Leftrightarrow M_{W_L} \ll M_{W_R})$$

experiment

$$\boxed{M_{W_R} \gtrsim 5\,\text{TeV}}$$ LHC

- what are Δ_L, Δ_R ?
- $\langle \Delta_L \rangle = 0, \quad \langle \Delta_R \rangle \neq 0$?

$\cancel{P}$ s-pont.

$$G_{LR} \xrightarrow[\langle \Delta_R \rangle]{} G_{SM} \xrightarrow[\langle \Phi \rangle]{} U(1)_{em}$$

$$\langle \Delta_R \rangle \gg \langle \Phi \rangle$$

SM = works great

$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad u_R,\ d_R$

$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad e_R$

$\Downarrow$

Δ_R : $\langle \Delta_R \rangle \neq 0$

gives mass to all

non SM particles

$\Leftrightarrow$ keep only SM states light :

$W_L^\pm$, Z, charged fermions, ν_L,

h

$\Leftrightarrow$ heavy states are !

$W_R^\pm$, Z_R (Z'), $\boxed{\nu_R !!}$,

new Higgs

$$\Downarrow$$

$$M_{W_R} \propto g \langle \Delta_R \rangle$$

$$M_{Z_R} \propto \, ? \, \langle \Delta_R \rangle$$

$$m_{\nu_R} \propto Y_\Delta \langle \Delta_R \rangle$$

$$\Downarrow$$

Δ_R couples to ν_R (Y_Δ)

$\Longleftrightarrow$ couples to $\ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$

Q. What is the $SU(2)$ content of Δ?

Δ = doublet, triplets, quartets -- ?

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \longleftrightarrow \begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

$$m_\nu \simeq m_e$$

"natural"

Curse of LR in '70s !

why (how) $m_\nu \ll m_e$?