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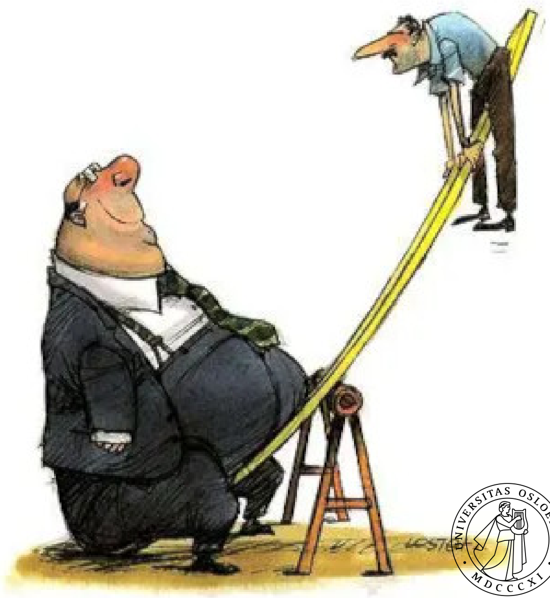
Neutrino Mass, Seesaws and Left-Right Symmetry



Halvor Melkild
halvor.melkild@fys.uio.no

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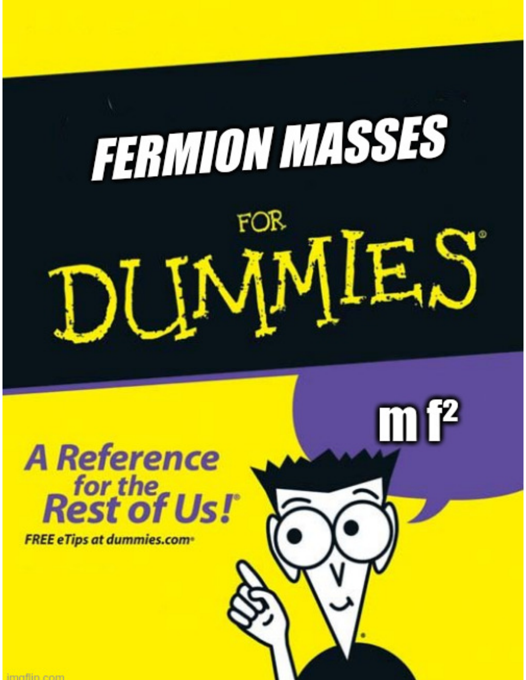
Fermion masses in the Standard Model


FERMION MASSES
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Fermion masses for dummies

$$\mathcal{L}_{\text{mass}} = mf^2$$

Fermion masses for dummies

$$\mathcal{L}_{\text{mass}} = mf^*f$$

Fermion masses for dummies

$$\mathcal{L}_{\text{mass}} = m f^\dagger f$$

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Fermion masses for dummies

$$\mathcal{L}_{\text{Dirac}} = m f^{\dagger} \gamma_0 f$$

Fermion masses for dummies

$$\mathcal{L}_{\text{Dirac}} = mf^\dagger \gamma_0 f$$

$$\mathcal{L}_{\text{Majorana}} = mf^\mathsf{T} f$$

Fermion masses for dummies

$$\mathcal{L}_{\text{Dirac}} = m f^\dagger \gamma_0 f$$

$$\mathcal{L}_{\text{Majorana}} = m f^{\mathsf{T}} \mathrm{i} \gamma_2 \gamma_0 f$$

Fermion masses for dummies

Chiral representation

$$f = \begin{pmatrix} f_\mathrm{L} \\ f_\mathrm{R} \end{pmatrix}$$

$$\gamma_0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}, \qquad \gamma_i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}. \tag{1}$$

Fermion masses for dummies

$$\mathcal{L}_{\text{Dirac}} = m(f_{\text{L}}^{\dagger} f_{\text{R}} + f_{\text{R}}^{\dagger} f_{\text{L}})$$

$$\mathcal{L}_{\text{Majorana}} = m(f_{\text{L}}^{\text{T}} \epsilon f_{\text{L}} - f_{\text{R}}^{\text{T}} \epsilon f_{\text{R}})$$

The Standard Model

Gauge group:

$$\mathcal{G}_{\mathrm{SM}} = SU(3)_{\mathrm{c}} \otimes SU(2)_{\mathrm{L}} \otimes U(1)_{\mathrm{Y}} \tag{2}$$

Quarks:

$$q_{\mathrm{L}}^{\alpha} = \begin{pmatrix} u_{\mathrm{L}}^{\alpha} \\ d_{\mathrm{L}}^{\alpha} \end{pmatrix}, \qquad u_{\mathrm{R}}^{\alpha}, \qquad d_{\mathrm{R}}^{\alpha}. \tag{3}$$

Leptons:

$$\ell_{\mathrm{L}} = \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix}, \qquad e_{\mathrm{R}}. \tag{4}$$

The End?

The Higgs mechanism

Quiz

The ABEGHHK’tH mechanism

Higgs Mechanism

Higgs boson:

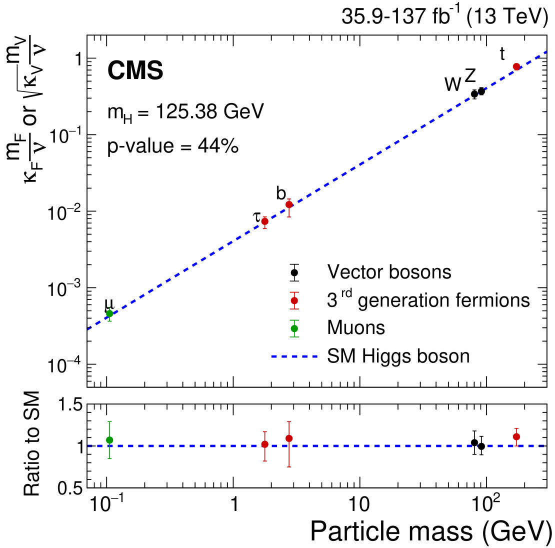
- Spin-0, Lorentz scalar
- $SU(2)_\mathrm{L}$ doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} 0 \\ v + h \end{pmatrix} . \tag{5}$$

Dirac masses and Higgs couplings

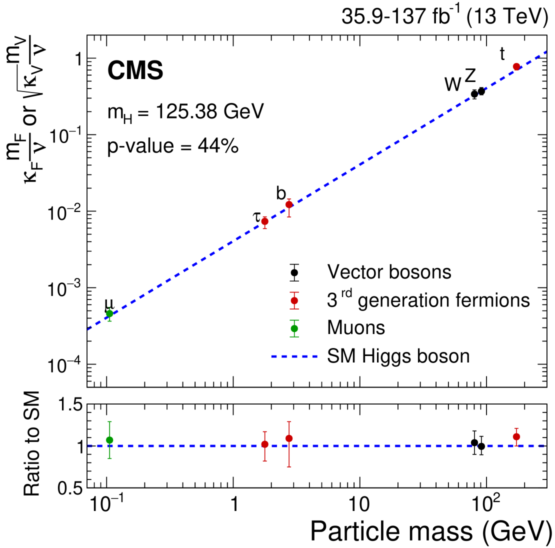
$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= y_e \ell_{\text{L}}^{\dagger} \Phi e_{\text{R}} \\ &= y_e (v + h) e_{\text{L}}^{\dagger} e_{\text{R}} \\ &= m_e e_{\text{L}}^{\dagger} e_{\text{R}} + \frac{m_e}{v} h e_{\text{L}}^{\dagger} e_{\text{R}}\end{aligned} \tag{6}$$

CMS (2020) [arXiv:2009.04363]



Higgs mechanism in the SM

- A single mass scale: $\langle \Phi \rangle = v$.
- Direct relation: $m \leftrightarrow y$.



Neutrino mass in the Standard Model

Neutrino mass in the Standard Model

$$\mathcal{G}_{\mathrm{SM}} = SU(3)_{\mathrm{c}} \otimes SU(2)_{\mathrm{L}} \otimes U(1)_{\mathrm{Y}} \tag{7}$$

$$q_{\mathrm{L}}^{\alpha} = \begin{pmatrix} u_{\mathrm{L}}^{\alpha} \\ d_{\mathrm{L}}^{\alpha} \end{pmatrix}, \qquad u_{\mathrm{R}}^{\alpha}, \qquad d_{\mathrm{R}}^{\alpha}, \tag{8}$$

$$\ell_{\mathrm{L}} = \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix}, \qquad e_{\mathrm{R}}, \tag{9}$$

Neutrino mass in the Standard Model

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$$\ell_{\mathrm{L}} = \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix}, \qquad e_{\mathrm{R}}, \qquad \nu_{\mathrm{R}}. \tag{9}$$

Neutrino mass in the Standard Model

Right-handed neutrino is sterile if it exists, so either

ν_R does **not** exist $\Rightarrow$ No Dirac mass

ν_R does exist $\Rightarrow$ Both Dirac and Majorana mass

Majorana mass from scalar triplet

We could introduce a triplet

$$\Delta = \begin{pmatrix} \delta^0 & \delta^+ \\ \delta^+ & \delta^{++} \end{pmatrix} \tag{10}$$

coupling as

$$\mathcal{L}_{\text{Triplet}} = y_\Delta \ell_L^T \Delta \ell_L \tag{11}$$

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Majorana mass from scalar triplet

Assume VEV for the neutral component

$$\langle \Delta \rangle = \begin{pmatrix} v_\Delta & 0 \\ 0 & 0 \end{pmatrix} \tag{12}$$

gives mass term

$$\mathcal{L}_{\text{Triplet}} = (y_\Delta v_\Delta) \nu_L^T \nu_L \tag{13}$$

Majorana mass from scalar triplet

Small VEV:

- Light lepton number violating scalars

Big VEV:

- Corrections to Higgs mass

Neutrino mass in the Standard Model

$$\mathcal{G}_{\mathrm{SM}} = SU(3)_{\mathrm{c}} \otimes SU(2)_{\mathrm{L}} \otimes U(1)_{\mathrm{Y}} \tag{14}$$

$$q_{\mathrm{L}}^{\alpha} = \begin{pmatrix} u_{\mathrm{L}}^{\alpha} \\ d_{\mathrm{L}}^{\alpha} \end{pmatrix}, \qquad u_{\mathrm{R}}^{\alpha}, \qquad d_{\mathrm{R}}^{\alpha}, \tag{15}$$

$$\ell_{\mathrm{L}} = \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix}, \qquad e_{\mathrm{R}}, \qquad \nu_{\mathrm{R}}. \tag{16}$$

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Neutrino mass in the Standard Model

Dirac mass

$$\begin{aligned} \mathcal{L}_{\text{Dirac},\nu} &= -y_\nu \ell_{\text{L}}^\dagger \epsilon \langle \Phi \rangle^* \nu_{\text{R}} \\ &= -m_{\text{D}} \nu_{\text{L}}^\dagger \nu_{\text{R}} \end{aligned} \tag{17}$$

Majorana mass

$$\mathcal{L}_{\text{Majorana},\nu} = -\frac{1}{2} m_{\text{M}} \nu_{\text{R}}^{\text{T}} \nu_{\text{R}} \tag{18}$$

Neutrino mass in the Standard Model

Neutrino mass matrix

$$\mathcal{L}_{\nu,\mathrm{mass}} \sim \begin{pmatrix} \nu_\mathrm{L} & \nu_\mathrm{R} \end{pmatrix} \begin{pmatrix} 0 & m_\mathrm{D} \\ m_\mathrm{D} & m_\mathrm{M} \end{pmatrix} \begin{pmatrix} \nu_\mathrm{L} \\ \nu_\mathrm{R} \end{pmatrix} \tag{19}$$

Mass eigenstates

$$\mathcal{L}_{\nu,\mathrm{mass}} \sim \begin{pmatrix} \nu & N \end{pmatrix} \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}, \quad \text{where} \quad \begin{pmatrix} \nu \\ N \end{pmatrix} = U \begin{pmatrix} \nu_\mathrm{L} \\ \nu_\mathrm{R} \end{pmatrix} \tag{20}$$

Seesaw mechanism

By assuming

$$m_{\mathrm{D}} \ll m_{\mathrm{M}} \tag{21}$$

we get

$$\begin{aligned} m_N &= m_{\mathrm{M}} \\ m_\nu &= -\frac{m_{\mathrm{D}}^2}{m_{\mathrm{N}}} \end{aligned} \tag{22}$$

Introducing generations

The SM contains three generations of fermions

$$\nu_{\mathrm{L}} \longrightarrow \begin{pmatrix} \nu_{e\mathrm{L}} \\ \nu_{\mu\mathrm{L}} \\ \nu_{\tau\mathrm{L}} \end{pmatrix} \tag{23}$$

The masses turns into mass matrices

$$\begin{pmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_{\mathrm{M}} \end{pmatrix} \longrightarrow \begin{pmatrix} 0 & M_{\mathrm{D}}^{\mathrm{T}} \\ M_{\mathrm{D}} & M_{\mathrm{M}} \end{pmatrix} \tag{24}$$

Introducing generations

$$
\begin{aligned}
M_N &= M_\mathrm{M} \\
M_\nu &= -M_\mathrm{D}^\mathrm{T} \frac{1}{M_\mathrm{N}} M_\mathrm{D}
\end{aligned}
\tag{25}
$$

Inverting the Seesaw

One generation:

$$m_\nu = -\frac{m_{\mathrm{D}}^2}{m_N} \quad \rightarrow \quad m_{\mathrm{D}} = \mathrm{i}\sqrt{m_\nu m_N} = y_\nu v \tag{26}$$

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Inverting the Seesaw

Three generations:

$$M_\nu = V^*_{\mathrm{PMNS}} m_\nu V^\dagger_{\mathrm{PMNS}} = -M^{\mathrm{T}}_{\mathrm{D}} \frac{1}{m_{\mathrm{N}}} M_{\mathrm{D}}. \tag{27}$$

To solve for M_{D} we notice that

$$I = (\mathrm{i} m_\nu^{-\frac{1}{2}} V^{\mathrm{T}}_{\mathrm{PMNS}} M^{\mathrm{T}}_{\mathrm{D}} m_N^{-\frac{1}{2}})(\mathrm{i} m_N^{-\frac{1}{2}} M_{\mathrm{D}} V_{\mathrm{PMNS}} m_\nu^{-\frac{1}{2}}) \tag{28}$$

and it follows that

$$M_{\mathrm{D}} = \mathrm{i}\sqrt{m_N} O \sqrt{m_\nu} V^\dagger_{PMNS}, \quad \text{where} \quad O \in O(3). \tag{29}$$

Casas, Ibarra (2001) [arXiv:hep-ph/0103065]

Right-handed neutrino in the Standard Model

- Mechanism to suppress m_ν
- Arbitrary mass scale m_M
- No direct relation between masses and couplings

The Left-Right Symmetric Model

The Standard Model

$$\mathcal{G}_{\mathrm{SM}} = SU(3)_{\mathrm{c}} \otimes SU(2)_{\mathrm{L}} \otimes U(1)_{\mathrm{Y}}$$

$$q_{\mathrm{L}}^{\alpha} = \begin{pmatrix} u_{\mathrm{L}}^{\alpha} \\ d_{\mathrm{L}}^{\alpha} \end{pmatrix}, \qquad u_{\mathrm{R}}^{\alpha}, \qquad d_{\mathrm{R}}^{\alpha},$$

$$\ell_{\mathrm{L}} = \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix}, \qquad e_{\mathrm{R}}, \qquad \nu_{\mathrm{R}}.$$

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The Left-Right Symmetric Model

$$\mathcal{G}_{\mathrm{LR}} = SU(3)_{\mathrm{c}} \otimes SU(2)_{\mathrm{L}} \otimes SU(2)_{\mathrm{R}} \otimes U(1)_{\mathrm{B-L}},$$

$$q_{\mathrm{L}}^{\alpha} = \begin{pmatrix} u_{\mathrm{L}}^{\alpha} \\ d_{\mathrm{L}}^{\alpha} \end{pmatrix}, \qquad q_{\mathrm{R}}^{\alpha} = \begin{pmatrix} u_{\mathrm{R}}^{\alpha} \\ d_{\mathrm{R}}^{\alpha} \end{pmatrix},$$

$$\ell_{\mathrm{L}} = \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix}, \qquad \ell_{\mathrm{R}} = \begin{pmatrix} \nu_{\mathrm{R}} \\ e_{\mathrm{R}} \end{pmatrix}.$$

Quiz

What are the weak hypercharges of the SM particles?

The Left-Right Symmetric Model

$$\mathcal{G}_{\mathrm{LR}} = SU(3)_{\mathrm{c}} \otimes SU(2)_{\mathrm{L}} \otimes SU(2)_{\mathrm{R}} \otimes U(1)_{\mathrm{B-L}} \otimes Z_2,$$

$$q_{\mathrm{L}}^{\alpha} = \begin{pmatrix} u_{\mathrm{L}}^{\alpha} \\ d_{\mathrm{L}}^{\alpha} \end{pmatrix}, \qquad q_{\mathrm{R}}^{\alpha} = \begin{pmatrix} u_{\mathrm{R}}^{\alpha} \\ d_{\mathrm{R}}^{\alpha} \end{pmatrix},$$

$$\ell_{\mathrm{L}} = \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix}, \qquad \ell_{\mathrm{R}} = \begin{pmatrix} \nu_{\mathrm{R}} \\ e_{\mathrm{R}} \end{pmatrix}.$$

Discrete LR symmetry

Parity:

$$f_{\mathrm{L}} \leftrightarrow f_{\mathrm{R}} \tag{30}$$

Charge conjugation

$$\begin{aligned} f &\leftrightarrow f^{c} \\ f_{\mathrm{L}} &\leftrightarrow \epsilon f_{\mathrm{R}}^{*} \end{aligned} \tag{31}$$

New particles in the LR model

Three new $SU(2)_\mathrm{R}$ gauge bosons

$$W^\mu_{\mathrm{R}\pm}, W^\mu_{\mathrm{R}0} \tag{32}$$

One "new" $U(1)_{\mathrm{B-L}}$ gauge boson

$$B^\mu_{\mathrm{B-L}} \tag{33}$$

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New particles in the LR model

One scalar bidoublet

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \qquad \Phi \longrightarrow U_\mathrm{L} \Phi U_\mathrm{R}^\dagger \tag{34}$$

Two scalar triplets

$$\Delta_\mathrm{R} = \begin{pmatrix} \delta_\mathrm{R}^0 & \delta_\mathrm{R}^+ \\ \delta_\mathrm{R}^+ & \delta_\mathrm{R}^{++} \end{pmatrix} \tag{35}$$

$$\Delta_\mathrm{R} \longrightarrow U_\mathrm{R} \Delta_\mathrm{R} U_\mathrm{R}^\mathrm{T}, \qquad \Delta_\mathrm{L} \longrightarrow U_\mathrm{L} \Delta_\mathrm{L} U_\mathrm{L}^\mathrm{T} \tag{36}$$

New particles in the LR model

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$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \qquad \Phi \longrightarrow U_\mathrm{L} \Phi U_\mathrm{R}^\dagger \tag{34}$$

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$$\Delta_\mathrm{R} \longrightarrow U_\mathrm{R} \Delta_\mathrm{R} U_\mathrm{R}^\mathrm{T}, \qquad \Delta_\mathrm{L} \longrightarrow U_\mathrm{L} \Delta_\mathrm{L} U_\mathrm{L}^\mathrm{T} \tag{36}$$

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The scalar potential

$$
\begin{aligned}
V_{\mathcal{C}} = &- \mu_1^2 \operatorname{Tr} \Phi^\dagger \Phi - \mu_2^2 \left(e^{i\delta_1} \operatorname{tr} \tilde{\Phi}^\dagger \Phi + h.c. \right) - \mu_3^2 \left(\operatorname{tr} \Delta_L^\dagger \Delta_L + \operatorname{tr} \Delta_R^\dagger \Delta_R \right) \\
&+ \lambda_1 \left(\operatorname{tr} \Phi^\dagger \Phi \right)^2 + \lambda_2 \left(e^{i\delta_2} \left(\operatorname{tr} \tilde{\Phi}^\dagger \Phi \right)^2 + h.c. \right) + \lambda_3 \operatorname{tr} \tilde{\Phi}^\dagger \Phi \operatorname{tr} \Phi^\dagger \tilde{\Phi} \\
&+ \lambda_4 \operatorname{tr} \Phi^\dagger \Phi \left(e^{i\delta_3} \operatorname{tr} \tilde{\Phi}^\dagger \Phi + h.c. \right) + \rho_1 \left(\left(\operatorname{tr} \Delta_L^\dagger \Delta_L \right)^2 + \left(\operatorname{tr} \Delta_R^\dagger \Delta_R \right)^2 \right) \\
&+ \rho_2 \left(\operatorname{tr} \Delta_L \Delta_L \operatorname{tr} \Delta_L^\dagger \Delta_L^\dagger + \operatorname{tr} \Delta_R \Delta_R \operatorname{tr} \Delta_R^\dagger \Delta_R^\dagger \right) \\
&+ \rho_3 \operatorname{tr} \Delta_L^\dagger \Delta_L \operatorname{tr} \Delta_R^\dagger \Delta_R + \rho_4 \left(e^{i\delta_4} \operatorname{tr} \Delta_L \Delta_L \operatorname{tr} \Delta_R^\dagger \Delta_R^\dagger + h.c. \right) \\
&+ (\text{6 terms coupling } \Phi \text{ and } \Delta)
\end{aligned}
\tag{37}
$$

Symmetry breaking

Neutral scalars acquire VEVs

$$\langle\Phi\rangle = \begin{pmatrix} v\cos\beta & 0 \\ 0 & v\sin\beta \end{pmatrix} \tag{38}$$

$$\Delta_R = \begin{pmatrix} v_R & 0 \\ 0 & 0 \end{pmatrix} \qquad \Delta_L = \begin{pmatrix} v_L & 0 \\ 0 & 0 \end{pmatrix} \tag{39}$$

To recover the Standard Model

$$v_1^2 + v_2^2 = v^2 \tag{40}$$

$$v_R \gg v \gg v_L \propto \frac{v}{v_R}v \tag{41}$$

Gauge boson mixing

Neutral gauge bosons will mix, similarly as in the SM.

Find mass eigenstates with masses

$$\begin{aligned} m_A^2 &= 0 \\ m_Z^2 &= m_{Z_{\mathrm{SM}}}^2 \left(1 + \mathcal{O}\left(\frac{v^2}{v_{\mathrm{R}}^2}\right)\right) \\ m_{Z'}^2 &\propto v_{\mathrm{R}}^2 \end{aligned} \tag{42}$$

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Gauge boson mixing

Also the charged gauge bosons will mix:

$$\begin{pmatrix} W_1^- \\ W_2^- \end{pmatrix} = \begin{pmatrix} 1 & -\xi \\ \xi^* & 1 \end{pmatrix} \begin{pmatrix} W_\mathrm{L}^- \\ W_\mathrm{R}^- \end{pmatrix}, \qquad \text{with} \qquad \xi \propto \frac{v^2}{v_\mathrm{R}^2}, \tag{43}$$

and similarly

$$\begin{aligned} m_{W_1}^2 &= m_{W_\mathrm{SM}}^2 \left(1 + \mathcal{O}\left(\frac{v^2}{v_\mathrm{R}^2}\right)\right) \\ m_{W_2}^2 &= g^2 v_\mathrm{R}^2 \end{aligned} \tag{44}$$

(CDF II, April 2022)

Yukawa couplings

Dirac term:

$$\mathcal{L}_{\text{Dirac}} = -Y \ell_{\text{L}}^{\dagger} \Phi \ell_{\text{R}} \tag{45}$$

Majorana term:

$$\mathcal{L}_{\text{Majorana}} = -Y_{\text{L}} \ell_{\text{L}}^{\text{T}} \Delta_{\text{L}} \ell_{\text{L}} - Y_{\text{R}} \ell_{\text{R}}^{\text{T}} \Delta_{\text{R}} \ell_{\text{R}} \tag{46}$$

Neutrino mass in the LR model

Dirac term:

$$\mathcal{L}_{\text{Dirac}} = -(v_1 Y)\nu_{\text{L}}^{\dagger}\nu_{\text{R}} \tag{47}$$

Majorana term:

$$\mathcal{L}_{\text{Majorana}} = -(v_{\text{L}} Y_{\text{L}})\nu_{\text{L}}^{\text{T}}\nu_{\text{L}} - (v_{\text{R}} Y_{\text{R}})\nu_{\text{R}}^{\text{T}}\nu_{\text{R}} \tag{48}$$

Neutrino mass in the LR model

Neutrino mass matrix

$$\mathcal{L}_{\nu,\text{mass}} \sim \begin{pmatrix} \nu_\text{L} & \nu_\text{R} \end{pmatrix} \begin{pmatrix} M_\text{L} & M_\text{D}^\text{T} \\ M_\text{D} & M_\text{R} \end{pmatrix} \begin{pmatrix} \nu_\text{L} \\ \nu_\text{R} \end{pmatrix} \tag{49}$$

Seesaw approximation

$$\begin{aligned} M_N &= M_\text{R} \\ M_\nu &= M_\text{L} - M_\text{D}^\text{T} \frac{1}{M_\text{R}} M_\text{D} \end{aligned} \tag{50}$$

Constraints from LR symmetry

Transformation of scalar fields:

$$\Phi \leftrightarrow \Phi^{\mathrm{T}}, \qquad \Delta_{\mathrm{L}} \leftrightarrow \Delta_{\mathrm{R}}^{*} \tag{51}$$

Constraints on Yukawa couplings:

$$Y = Y^{\mathrm{T}}, \qquad Y_{\mathrm{L}} = Y_{\mathrm{R}}^{*} \tag{52}$$

Neutrino mass in the LR model

Constraints on mass matrices

$$M_{\mathrm{D}} = M_{\mathrm{D}}^{\mathrm{T}}, \qquad M_{\mathrm{L}} = \frac{v_{\mathrm{L}}}{v_{\mathrm{R}}} M_{\mathrm{R}}^{*} \tag{53}$$

Neutrino mass

$$M_{\nu} = \frac{v_{\mathrm{L}}}{v_{\mathrm{R}}} M_{N} - M_{\mathrm{D}} \frac{1}{M_{N}} M_{\mathrm{D}} \tag{54}$$

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Neutrino mass in the LR model

Neutrino mass

$$M_\nu = \frac{v_L}{v_R} M_N - M_D \frac{1}{M_N} M_D \tag{55}$$

Now we can solve directly for M_D

$$M_D = M_N \sqrt{\frac{v_L}{v_R} - \frac{1}{M_N} M_\nu} \tag{56}$$

Nemevšek, Senjanović, Tello (2013) [arXiv:1211.2837]

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Summary

- Neutrino mass requires a new mass scale
- Seesaw mechanism explains light neutrinos through a high mass scale
- LR model connects the neutrino mass to the LR breaking scale
- We get a predictive relationship between couplings, masses and mixings

Summary

Neutrino mass could be a feature, not a bug!

Halvor Melkild
E-mail: halvor.melkild@fys.uio.no
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