Scotogenic seesaw and baryogenesis

with gauged Baryon number

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Focus on
arXiv:2205.05762
In collaboration with
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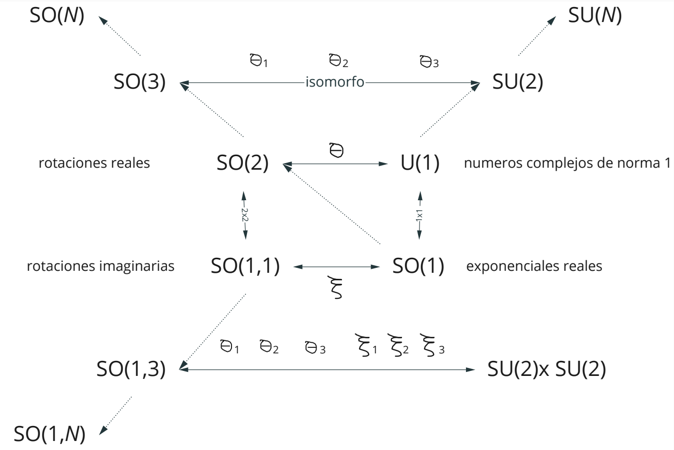
Model building

Lie groups



$$U = \exp\left(i \sum_j T_j \theta^j\right), \tag{1}$$

where θ^j are the parameters of the transformation and T_j are the generators.

SO(1)

Consider the 1×1

$$K = -i\,, \tag{2}$$

which generates an element of dilaton group , SO(1), $R(\xi)$

$$\lambda(\xi) = \mathrm{e}^{\xi}\,, \tag{3}$$

which are just the group of the real exponentials. Such a number can be transformed as

$$x \rightarrow x' = \mathrm{e}^{\xi}\, x\,, \tag{4}$$

that corresponds to a boost by e^{ξ}. We can defin the invariant scalar product just as the division of real numbers, such that

$$x \cdot y \rightarrow x' \cdot y' \equiv \frac{x'}{y'} = \frac{\mathrm{e}^{\xi}\, x}{\mathrm{e}^{\xi}\, y} = \frac{x}{y} = x \cdot y\,. \tag{5}$$

SO(1, 1)

Queremos obtener una representación 2×2 del álgebra

$$K = \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \to K^2 = -\mathbf{1}\,, \tag{6}$$

que genera un elemento del grupo SO(1, 1) con *parámetro* ξ

$$\Lambda = \exp\left(i\xi K\right) = \begin{pmatrix} \cosh\xi & \sinh\xi \\ \sinh\xi & \cosh\xi \end{pmatrix}, \,. \tag{7}$$

La transformación de una coordenada temporaloide y otra espacialoide ($c = 1$)

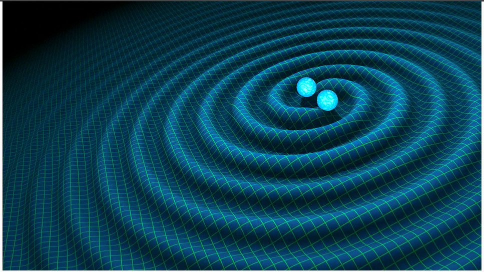
$$\begin{pmatrix} t \\ x \end{pmatrix} = \begin{pmatrix} x^0 \\ x^1 \end{pmatrix} \to \begin{pmatrix} x'^0 \\ x'^1 \end{pmatrix} \begin{pmatrix} \cosh\xi & \sinh\xi \\ \sinh\xi & \cosh\xi \end{pmatrix} \begin{pmatrix} x^0 \\ x^1 \end{pmatrix}$$

$$\cosh \xi = \gamma = \frac{1}{\sqrt{1 - v^2}}$$

Special: parameter ξ or v is constant, e.g, inertial system invariance: *Global* conservation of E and $\boldsymbol{p}$ (still action at a distance!)

General: parameter $\xi(t, \boldsymbol{x})$ or $v(t, \boldsymbol{x})$ is constant, e.g, accelerated system invariance: *Local* conservation of E and $\boldsymbol{p}$

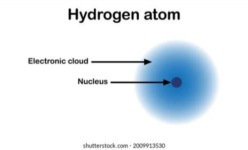
Inestability of binary particle systems



Gravitational wave discovery by LIGO

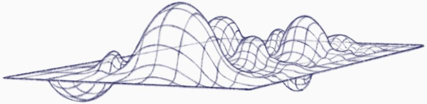
credits: science.org

Noether's paradigm

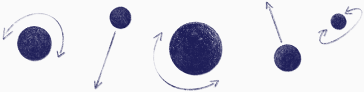


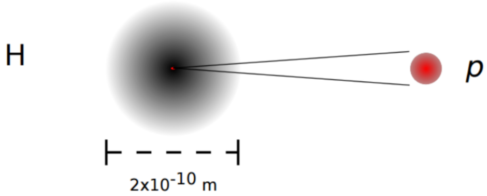
What is a ~~particle~~ *wavicle*? `https://www.quantamagazine.org/what-is-a-particle-20201112/`

Is a "Quantum Excitation of a Field"



Is a "Irreducible Representation of a Group"



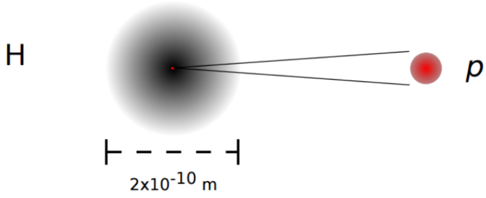

H
p
2x10-10 m

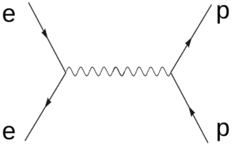
Interacción → Fuerza = Δ**p**/Δt

Introducción

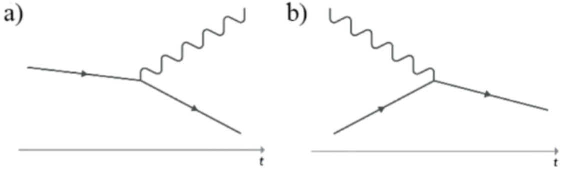
Campos de materia

Campos de radiación





doi:10.1088/1742-6596/1287/1/012045



Emisión absorción

Interacción → Fuerza = Δ**p**/Δt

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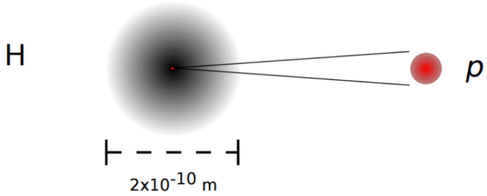

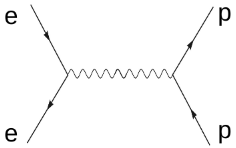

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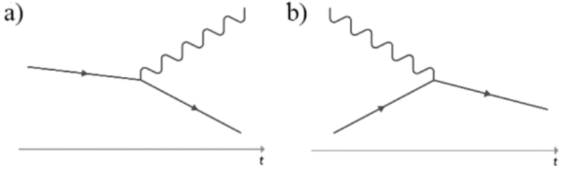
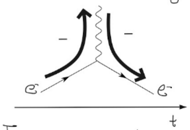


Emisión absorción

$$e^- \rightarrow e^{-iEt}$$

$$e^+ \rightarrow e^{-iE(-t)}$$

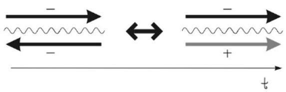
Single charge

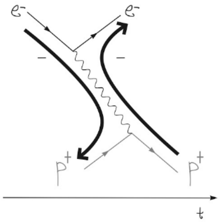


Fuerza $\frac{\Delta \vec{p}}{\Delta t} \neq 0$

$(e^-)^* = e^+$

fotón neutro





Under a general Lorentz transformation we have.

$$A^{\mu}(x) \to A'^{\mu}(x) = \Lambda^{\mu}{}_{\nu} A^{\nu}(\Lambda^{-1}x). \tag{8}$$

A pure underscript 4-vector is

$$\partial_{\mu} = \frac{\partial}{\partial x^{\mu}} = \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) = (\partial_0, \boldsymbol{\nabla}). \tag{9}$$

From

$$\frac{1}{x'^{\mu}} = \left(\Lambda^{-1}\right)^{\nu}{}_{\mu} \frac{1}{x^{\nu}}\,, \tag{10}$$

the tranformation properties for a $\partial_{\mu} = \partial/\partial x^{\mu}$, are

$$\partial'_{\mu} = \left(\Lambda^{-1}\right)^{\nu}{}_{\mu} \partial_{\nu}\,. \tag{11}$$

In this way, the invariant scalar product between the 4-vector field and the four-gradient is just

$$\partial_\mu A^\mu \rightarrow \partial'_\mu A'^\mu = \partial_\mu A^\mu \,. \tag{12}$$

Name	Symbol	SU(N)
scalar N-plet	Ψ	$U\Psi$
scalar anti-N-plet	$\Psi^\dagger$	$\Psi^\dagger U^\dagger$

Name	Symbol	Lorentz
Photon	A^μ	$\Lambda^\mu{}_\nu A^\nu$
4-gradient	∂_μ	$\partial_\nu \left(\Lambda^{-1}\right)^\nu{}_\mu$

Table 1: Scalar products: $\Psi^\dagger\Psi$, $\partial_\mu A^\mu\,, \quad A^\nu A_\nu\,, \quad \partial_\mu\partial^\mu$

Name	Symbol	Lorentz	$U(1)$
e_L: electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta}\xi_\alpha$
$(e_L)^\dagger$: positron right	$(\xi_\alpha)^\dagger = \xi^\dagger_{\dot\alpha}$	$\xi^\dagger_{\dot\beta}\left[S^\dagger\right]^{\dot\beta}{}_{\dot\alpha}$	$\xi^\dagger_{\dot\alpha} e^{-i\theta}$
e_R: electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\,\dot\alpha}$	$\left[\left(S^{-1}\right)^\dagger\right]^{\dot\alpha}{}_{\dot\beta}\eta^{\dagger\,\dot\beta}$	$e^{i\theta}\eta^{\dagger\,\dot\alpha}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 2: electron components

Scalar products

- ~~U(1)~~ Majorana scalars: $\xi^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\xi^{\dagger\dot\alpha}$, $\eta^\alpha\eta_\alpha + \eta^\dagger_{\dot\alpha}\eta^{\dagger\dot\alpha}$.
- Dirac scalar: $\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\eta^{\dagger\,\dot\alpha}$.
- Tensor under subgroup SL(2, C) but vector under SO(1, 3): $S^{\dagger\dot\alpha}{}_{\dot\beta}\bar\sigma^{\mu\,\dot\beta\beta}S_\beta{}^\alpha = \Lambda^\mu{}_\nu\bar\sigma^{\nu\,\dot\alpha\alpha}$

Name	Symbol	Lorentz	$U(1)$
e_L: electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta}\xi_\alpha$
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$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 3: electron components

General theory: QED $\to D_\mu = i\partial_\mu - ieA_\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$\xi^\alpha \to \xi'^\alpha = e^{i\theta(x)}\xi^\alpha \qquad \eta_\alpha \to \eta'_\alpha = e^{-i\theta(x)}\eta_\alpha$$

$$D_\mu\xi^\alpha \to (D_\mu\xi^\alpha)' = e^{i\theta(x)}D_\mu\xi^\alpha \qquad D_\mu\eta_\alpha \to (D_\mu\eta_\alpha)' = e^{-i\theta(x)}D_\mu\eta_\alpha$$

$$\mathcal{L} = i\xi^\dagger_{\dot\alpha}\bar\sigma^{\mu\,\dot\alpha\alpha}D_\mu\xi_\alpha + i\eta^\alpha\sigma^\mu_{\alpha\dot\alpha}D_\mu\eta^{\dagger\,\dot\alpha} - m\left(\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\eta^{\dagger\,\dot\alpha}\right) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

Name	Symbol	Lorentz	$U(1)$
e_L: electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta}\xi_\alpha$
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$$\mathcal{L} = i\overline{\psi}\gamma^\mu D_\mu\psi - m\overline{\psi}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\,.$$

Dirac spinor

$$\psi = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$$

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \overline{\sigma}^\mu & 0 \end{pmatrix}$$

$$\overline{\psi} = \psi^\dagger\gamma^0\,.$$

17 years later... (stages of grief $\rightarrow$ 1967)

Not mass, not charge

Field	Lorentz	SU(2)$_L$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	$\mathbf{2}$

Denial

$$\mathcal{L} = i\,(L)^\dagger\,\overline{\sigma}^\mu\,D_\mu L - \tfrac{1}{4}W^i_{\mu\nu}W_i^{\mu\nu}$$

$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ 17 years later... (stages of grief $\rightarrow$ 1967)

Not mass, hypercharge,

Field	Lorentz	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	$\mathbf{2}$	$-1/2$

Denial

$$\mathcal{L} = i\,(L)^\dagger\,\overline{\sigma}^\mu D_\mu L - \tfrac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$SU(2)_L \times U(1)_Y$ 17 years later... (stages of grief $\rightarrow$ 1967)

Not mass, hypercharge, not Dirac

Field	Lorentz	$SU(2)_L$	$U(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	$\mathbf{2}$	$-1/2$
$(e_R)^\dagger$	η^α	$\mathbf{1}$	-1

Denial

$$\mathcal{L} = i\,(L)^\dagger\,\overline{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i\,(e_R)^\dagger\,\sigma^\mu D_\mu e_R$$

$SU(2)_L \times U(1)_Y$ 17 years later... (stages of grief $\to$ 1967)

Higgs mechanism with tachyonic mass ($\mu^2 < 0$) and condensate

Field	Lorentz	$SU(2)_L$	$U(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	$\mathbf{2}$	$-1/2$
$(e_R)^\dagger$	η^α	$\mathbf{1}$	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	$\mathbf{2}$	$1/2$

Contempt

$$\mathcal{L} = i\,(L)^\dagger\,\overline{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i\,(e_R)^\dagger\,\sigma^\mu D_\mu e_R + (e_R)^\dagger\,\Phi^\dagger L - (D^\mu\Phi)^\dagger\, D_\mu\Phi - \mu^2 \Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2$$

$SU(2)_L \times U(1)_Y$ 17 years later... (stages of grief → 1967)

Higgs mechanism with tachyonic mass ($\mu^2 < 0$) and condensate

Field	Lorentz	$SU(2)_L$	$U(1)_Y$
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$(e_R)^\dagger$	η^α	**1**	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	**2**	$1/2$

Contempt

$$\mathcal{L} = i(L)^\dagger \overline{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + (e_R)^\dagger \Phi^\dagger L - (D^\mu\Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2$$

$$\Phi \to \Phi' = \exp\left[i\frac{\tau^i}{2}\theta_i(x)\right]\Phi = \frac{1}{\sqrt{2}}[H(x)+v]$$

$$\mathcal{L} = i\overline{\psi}\gamma^\mu\partial\psi - m_e\overline{\psi}\psi - i(\nu_L)^\dagger \overline{\sigma}^\mu \partial_\mu \nu_L + (e_R)^\dagger \Phi^\dagger L - (D^\mu\Phi)^\dagger D_\mu\Phi - \mu^2\Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2 - \mathcal{L}_{\text{gauge}} + Z\nu\nu + m_e\overline{\psi}$$

$SU(2)_L \times U(1)_Y$ 17 years later... (stages of grief → 1971)

Z and W phenomenology and discovery

Field	Lorentz	$SU(2)_L$	$U(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**	$-1/2$
$(e_R)^\dagger$	η^α	**1**	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	**2**	$1/2$

Bargaining

$$\mathcal{L} = i(L)^\dagger \overline{\sigma}^\mu D_\mu L - \tfrac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + (e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$

$$\Phi \to \Phi' = \exp\left[i\frac{\tau^i}{2}\theta_i(x)\right] \Phi = \frac{1}{\sqrt{2}}[H(x) + v]$$

$$\mathcal{L} = i\overline{\psi}\gamma^\mu \partial\psi - m_e \overline{\psi}\psi - i(\nu_L)^\dagger \overline{\sigma}^\mu \partial_\mu \nu_L + (e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2 - \mathcal{L}_{\text{gauge}} + Z\nu\nu + m_e\overline{\psi}$$

$SU(2)_L \times U(1)_Y$ 17 years later... (stages of grief $\to$ 1982)

Hierarchy problem

Field	Lorentz	$SU(2)_L$	$U(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**	$-1/2$
$(e_R)^\dagger$	η^α	**1**	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	**2**	$1/2$

Depression

$$\mathcal{L} = i(L)^\dagger \overline{\sigma}^\mu D_\mu L - \tfrac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + (e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$

$$\Phi \to \Phi' = \exp\left[i\frac{\tau^i}{2}\theta_i(x)\right] \Phi = \frac{1}{\sqrt{2}}[H(x) + v]$$

$$\mathcal{L} = i\overline{\psi}\gamma^\mu \partial\psi - m_e \overline{\psi}\psi - i(\nu_L)^\dagger \overline{\sigma}^\mu \partial_\mu \nu_L + (e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2 - \mathcal{L}_{\text{gauge}} + Z\nu\nu + m_e\overline{\psi}$$

$SU(2)_L \times U(1)_Y$ 17 years later... (stages of grief $\to$ 2012)

Higgs discovery!

Field	Lorentz	$SU(2)_L$	$U(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	$\mathbf{2}$	$-1/2$
$(e_R)^\dagger$	η^α	$\mathbf{1}$	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	$\mathbf{2}$	$1/2$

Acceptance

$$\mathcal{L} = i(L)^\dagger \overline{\sigma}^\mu D_\mu L - \tfrac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + (e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$

$$\Phi \to \Phi' = \exp\left[i\frac{\tau^i}{2}\theta_i(x)\right] \Phi = \frac{1}{\sqrt{2}}[H(x) + v]$$

$$\mathcal{L} = i\overline{\psi}\gamma^\mu \partial \psi - m_e \overline{\psi}\psi - i(\nu_L)^\dagger \overline{\sigma}^\mu \partial_\mu \nu_L + (e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2 - \mathcal{L}_{\text{gauge}} + Z\nu\nu + m_e\overline{\psi}$$