# Scotogenic seesaw and baryogenesis

## with gauged Baryon number


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**Focus on**
arXiv:2205.05762
In collaboration with


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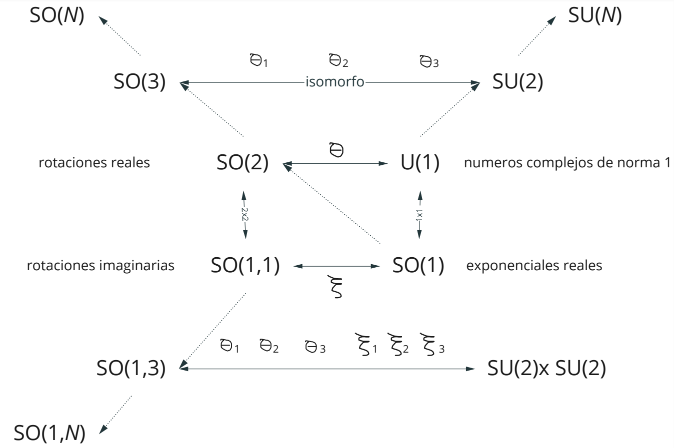
# Least Action

# SO(3) **scalar product**

$$L = \frac{1}{2} m v^2 - V(|\boldsymbol{r}|) = \frac{1}{2} m \boldsymbol{v} \cdot \boldsymbol{v} - V(|\boldsymbol{r}|)$$

# Lie groups




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

where $\theta^j$ are the parameters of the transformation and $T_j$ are the generators.

# SO(1)

Consider the $1 \times 1$

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

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

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

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

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

Queremos obtener una representación $2 \times 2$ 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* $\xi$

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

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

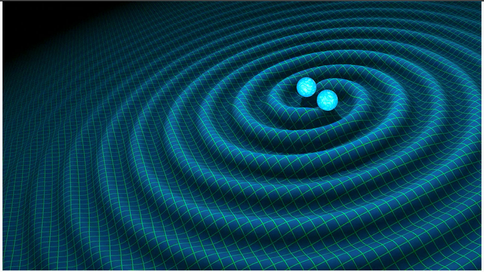
$$\begin{pmatrix} t \\ x \end{pmatrix} = \begin{pmatrix} x^0 \\ x^1 \end{pmatrix} \to \begin{pmatrix} x'^0 \\ x'^1 \end{pmatrix} \begin{pmatrix} \cosh\xi & \sinh\xi \\ \sinh\xi & \cosh\xi \end{pmatrix} \begin{pmatrix} x^0 \\ x^1 \end{pmatrix}$$

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

**Special**: parameter $\xi$ 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

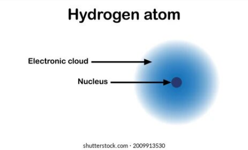
New

UNIVERSIDAD DE ANTIOQUIA

credits: science.org

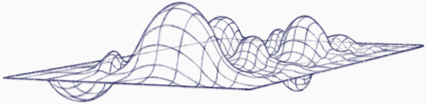
Noether's paradigm

# U(1): **From special $\theta$ to general $\theta(t, \boldsymbol{x})$**

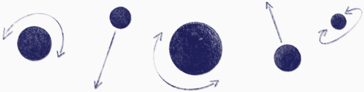



What is a ~~particle~~ *wavicle*? `https://www.quantamagazine.org/what-is-a-particle-20201112/`

**Is a “Quantum Excitation of a Field”**



**Is a “Irreducible Representation of a Group”**



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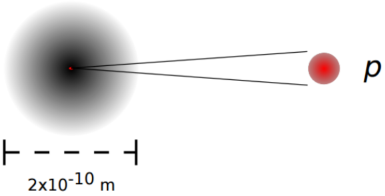
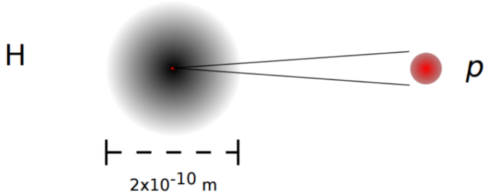


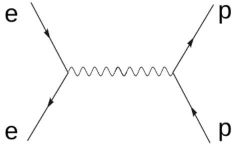
# Interacción → Fuerza = Δ**p**/Δt

Introducción

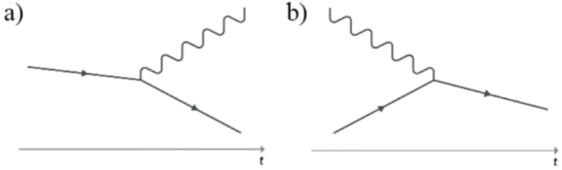
campos de materia ⟶

Campos de radiación




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



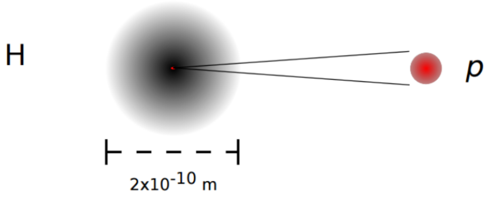

Emisión absorción

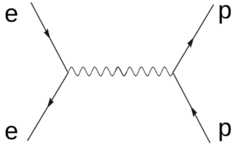
## Interacción → Fuerza = $\Delta \mathbf{p}/\Delta t$

Introducción

Campos de materia

Campos de radiación

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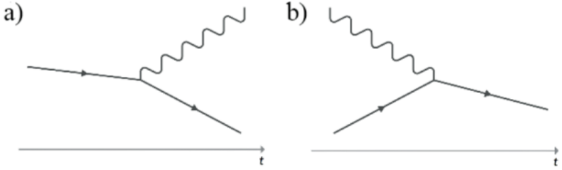
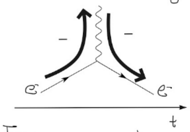



Emisión absorción

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

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

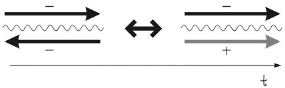
Single charge

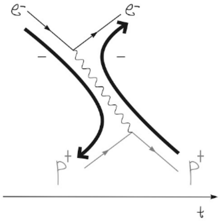



Fuerza $\frac{\Delta \vec{P}}{\Delta t} \neq 0$

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

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

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

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

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

**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 | $\xi_\alpha$ | $S_\alpha{}^\beta \xi_\beta$ | $e^{i\theta}\xi_\alpha$ |
| $(e_L)^\dagger$: 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 | $\eta^\alpha$ | $\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$ | $e^{-i\theta}\eta^\alpha$ |

**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): $S^{\dagger\dot\alpha}{}_{\dot\beta}\,\overline{\sigma}^{\mu\,\dot\beta\beta}S_\beta{}^\alpha = \Lambda^\mu{}_\nu\overline{\sigma}^{\nu\,\dot\alpha\alpha}$

| Name | Symbol | Lorentz | $U(1)$ |
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| $e_R$: 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 | $\eta^\alpha$ | $\eta^\beta{\left[S^{-1}\right]_\beta}^\alpha$ | $e^{-i\theta}\eta^\alpha$ |

**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 | $U(1)$ |
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$$\mathcal{L} = i\bar\psi\gamma^\mu D_\mu\psi - m\bar\psi\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\,.$$

## Dirac spinor

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

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

$$\bar\psi = \psi^\dagger\gamma^0\,.$$

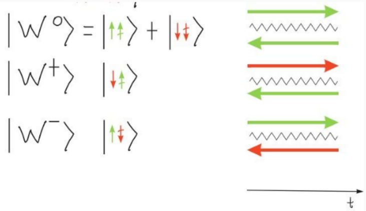
# $SU(2)_L \quad \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu$ : 17 years later... (stages of grief $\to$ 1967)

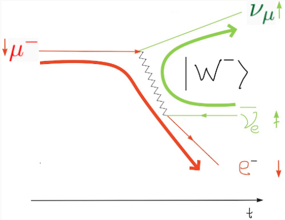
## Not mass, not charge

| Field | Lorentz | $SU(2)_L$ |
|---|---|---|
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $\xi_\alpha$ | **2** |
| | | |

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

## Denial



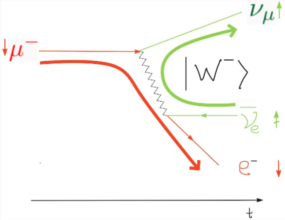



# $SU(2)_L \times U(1)_Y \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$ : 17 years later... (stages of grief → 1967)

## Not mass, hypercharge,

| Field | Lorentz | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $\xi_\alpha$ | **2** | $-1/2$ |
| | | | |

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

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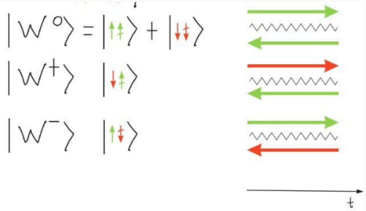

# $SU(2)_L \times U(1)_Y \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$ : 17 years later... (stages of grief → 1967)

## Not mass, hypercharge, not Dirac

| Field | Lorentz | $SU(2)_L$ | $U(1)_Y$ |
| --- | --- | --- | --- |
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $\xi_\alpha$ | $\mathbf{2}$ | $-1/2$ |
| $(e_R)^\dagger$ | $\eta^\alpha$ | $\mathbf{1}$ | $-1$ |

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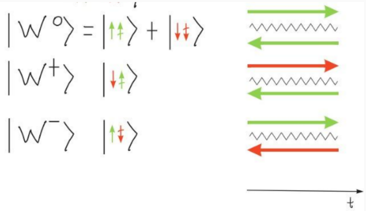
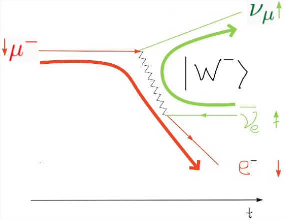



$$\mathcal{L} = i(L)^\dagger \overline{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R$$



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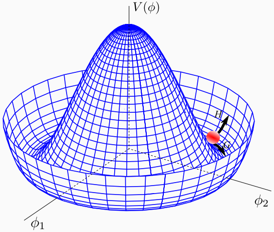
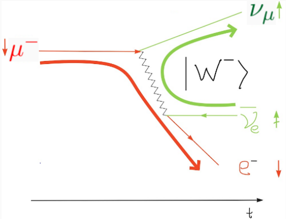
## Higgs mechanism: tachyonic mass $\mu^2 < 0$, and condensate

| Field | Lorentz | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $\xi_\alpha$ | **2** | $-1/2$ |
| $(e_R)^\dagger$ | $\eta^\alpha$ | **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




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



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## Contempt

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix},$$

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

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

$$\mathcal{L} = i\overline{\psi}\gamma^\mu \partial\psi - m_e \overline{\psi}\psi - i(\nu_L)^\dagger \overline{\sigma}^\mu \partial_\mu \nu_L + \frac{1}{2}\partial^\mu H \partial_\mu H + \frac{e}{\cos\theta_W \sin\theta_W} \overline{\nu_L}\nu_L Z_\mu + \cdots$$

$$-\frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu-} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v}\overline{\psi}\psi H$$

# $SU(2)_L \times U(1)_Y \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$ : 21 years later... (stages of grief $\to$ 1971)

## $Z$ and $W$ phenomenology and discovery

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

## Bargaining

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

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

$$\mathcal{L} = i\bar{\psi}\gamma^\mu \partial \psi - m_e \bar{\psi}\psi - i(\nu_L)^\dagger \bar{\sigma}^\mu \partial_\mu \nu_L + \frac{1}{2}\partial^\mu H \partial_\mu H + \frac{e}{\cos\theta_W \sin\theta_W} \overline{\nu_L} \nu_L Z_\mu + \cdots$$

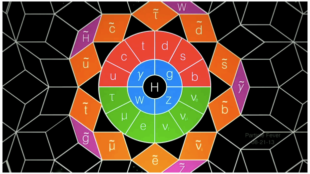
$$-\frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu -} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v}\bar{\psi}\psi H$$

# $SU(2)_L \times U(1)_Y \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$ : 32 years later... (stages of grief → 1982)

## Hierarchy problem

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

## Depression



credit: quantumdiaries.org

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

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

$$\mathcal{L} = i\overline{\psi}\gamma^\mu \partial\psi - m_e \overline{\psi}\psi - i(\nu_L)^\dagger \overline{\sigma}^\mu \partial_\mu \nu_L + \frac{1}{2}\partial^\mu H \partial_\mu H + \frac{e}{\cos\theta_W \sin\theta_W} \overline{\nu_L}\nu_L Z_\mu + \cdots$$

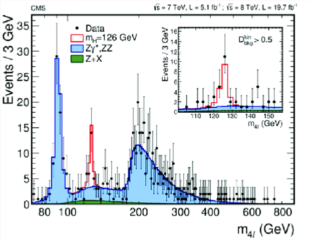
$$-\frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu -} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v}\overline{\psi}\psi H$$

# $SU(2)_L \times U(1)_Y \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$ : 62 years later... (stages of grief → 2012)

## Higgs discovery!

| Field | Lorentz | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $\xi_\alpha$ | **2** | $-1/2$ |
| $(e_R)^\dagger$ | $\eta^\alpha$ | **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** | $1/2$ |

## Acceptance




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

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

$$\mathcal{L} = i\overline{\psi}\gamma^\mu \partial\psi - m_e \overline{\psi}\psi - i(\nu_L)^\dagger \overline{\sigma}^\mu \partial_\mu \nu_L + \frac{1}{2}\partial^\mu H \partial_\mu H + \frac{e}{\cos\theta_W \sin\theta_W} \overline{\nu_L}\nu_L Z_\mu + \cdots$$

$$-\frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu -} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v}\overline{\psi}\psi H$$