FISICA DE LAS INTERACCIONES FUNDAMENTALES

1ER CUATRIMESTRE 2026

CLASE 16

RODOLFO SASSOT

CLASE 16: Unificación electro-débil, ruptura espontánea de simetría

Temas: Teoría electro-débil, fenomenología, ruptura espontánea, mecanismo de Higgs.

lista de problemas de $SU(2)_L$*:*

$M_W \neq 0 \quad M_{Z^0} \neq 0$ términos de masa explícitos $\sim M_W^2 W_\mu W^\mu$ romperían la invariancia de gauge

$M \equiv \begin{pmatrix} m_\nu & 0 \\ 0 & m_e \end{pmatrix}$ términos de masa (distintas) para los fermiones romperían la invariancia de gauge

$W^\pm$ tienen carga eléctrica, cómo interactúan con QED?

hay interacciones débiles sin intercambio de carga entre las componentes R de los quarks

Teoría electro-débil (1959):

~ electromagnetismo e interacciones débiles como dos aspectos de la misma teoría $U(1) \times SU(2)_L$

U(1) no es QED, su campo de gauge B_μ no es lo que llamamos A_μ

W_μ^3 de $SU(2)_L$, no es el Z_μ

A. Salam, S. Weinberg, S. Glashow

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Teoría electro-débil:

$$\mathcal{L}_{int}^{QED} \sim q\,\overline{\psi}_e \gamma^\mu \psi_e A_\mu \qquad \mathcal{L}_{int}^{U(1)} \sim \frac{g_1}{2}\left[\, Y_L^e\, \overline{e}_L \gamma^\mu e_L + Y_R^e\, \overline{e}_R \gamma^\mu e_R + Y_L^\nu\, \overline{\nu}_L \gamma^\mu \nu_L + Y_R^\nu\, \overline{\nu}_R \gamma^\mu \nu_R \,\right] B_\mu$$

$$Y_L^e = Y_L^\nu = Y_L \qquad Y_R^e = Y_R \qquad Y_R^\nu = 0$$

$$W_\mu^\pm \equiv \frac{-1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \qquad \mathcal{L}_{int}^{SU(2)_L} \sim \frac{g_2}{2}\left[-\sqrt{2}\,\overline{\nu}_L \gamma^\mu e_L\, W_\mu^+ - \sqrt{2}\,\overline{e}_L \gamma^\mu \nu_L\, W_\mu^- + \overline{\nu}_L \gamma^\mu \nu_L\, W_\mu^3 + \overline{e}_L \gamma^\mu e_L\, W_\mu^3\right]$$

$$\underbrace{\left(\frac{g_1}{2} Y_L B_\mu + \frac{g_2}{2} W_\mu^3\right)}_{\sim Z_\mu^0} \overline{\nu}_L \gamma^\mu \nu_L \qquad \underbrace{\left(\frac{g_2}{2} B_\mu - \frac{g_1}{2} Y_L W_\mu^3\right)}_{\sim A_\mu} (\overline{e}_L \gamma^\mu e_L + \overline{e}_R \gamma^\mu e_R)$$

$$\left.\begin{array}{lll} U(1) & B_\mu & e_L, e_R, \nu_L \\ SU(2)_L & W_\mu^3 & \end{array}\right\} \leftrightarrow \left\{\begin{array}{l} A_\mu \equiv (g_2 B_\mu - g_1 Y_L W_\mu^3)\,/\,(g_2^2 + g_1^2 Y_L^2)^{1/2} \\ Z_\mu^0 \equiv (g_1 Y_L B_\mu + g_2 W_\mu^3)\,/\,(g_2^2 + g_1^2 Y_L^2)^{1/2} \end{array}\right.$$

$$\left.\begin{array}{ll} W_\mu^2 & e_L, \nu_L \\ W_\mu^1 & \end{array}\right\} \leftrightarrow \left\{\begin{array}{l} W_\mu^+ \equiv -\frac{1}{\sqrt{2}}(W_\mu^1 - iW_\mu^2) \\ W_\mu^- \equiv -\frac{1}{\sqrt{2}}(W_\mu^1 + iW_\mu^2) \end{array}\right.$$

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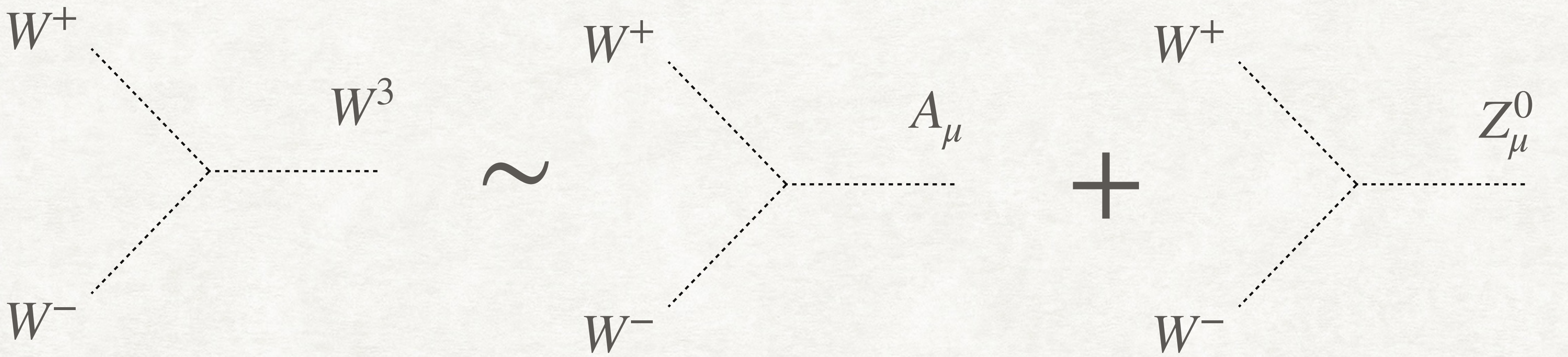
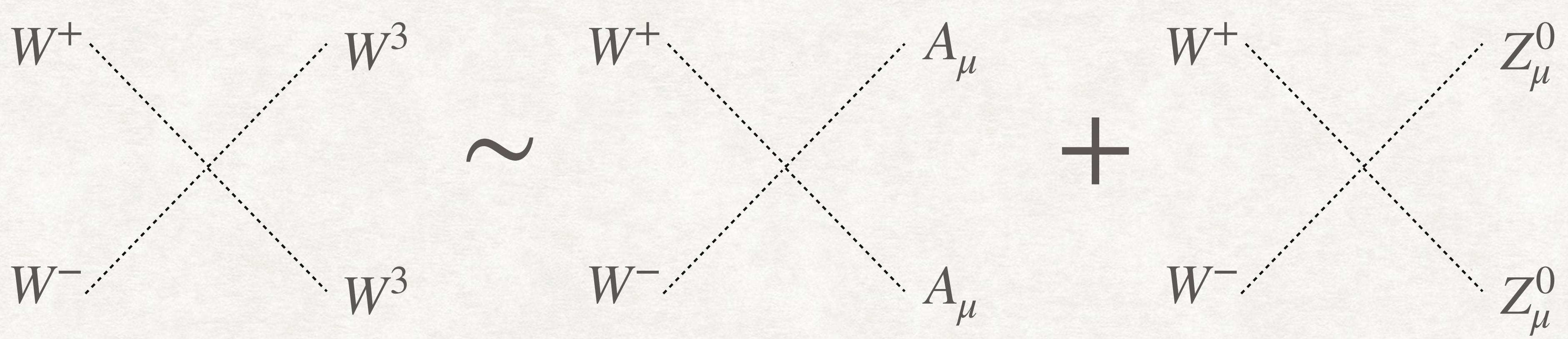
Teoría electro-débil:





$$\sum_i W^i_{\mu\nu}W^{\mu\nu}_i = \sum_i \Big((\partial_\mu W^i_\nu - \partial_\nu W^i_\mu) + g W^j_\mu W^k_\nu \epsilon_{ijk}\Big)\Big((\partial^\mu W^\nu_i - \partial^\nu W^\mu_i) + g W^\mu_j W^\nu_k \epsilon_{ijk}\Big)$$

$$\epsilon_{1jk}\epsilon_{1rs} = \delta^r_j\delta^s_k - \delta^s_j\delta^r_k$$

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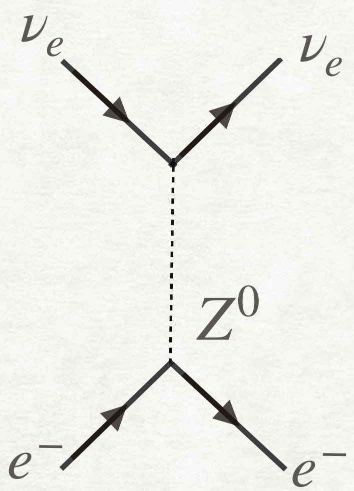
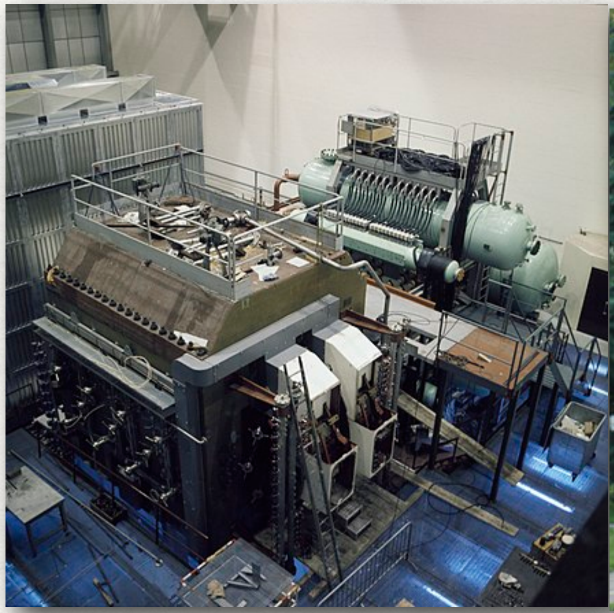
fenomenología:

1973 Gargamelle (CERN)

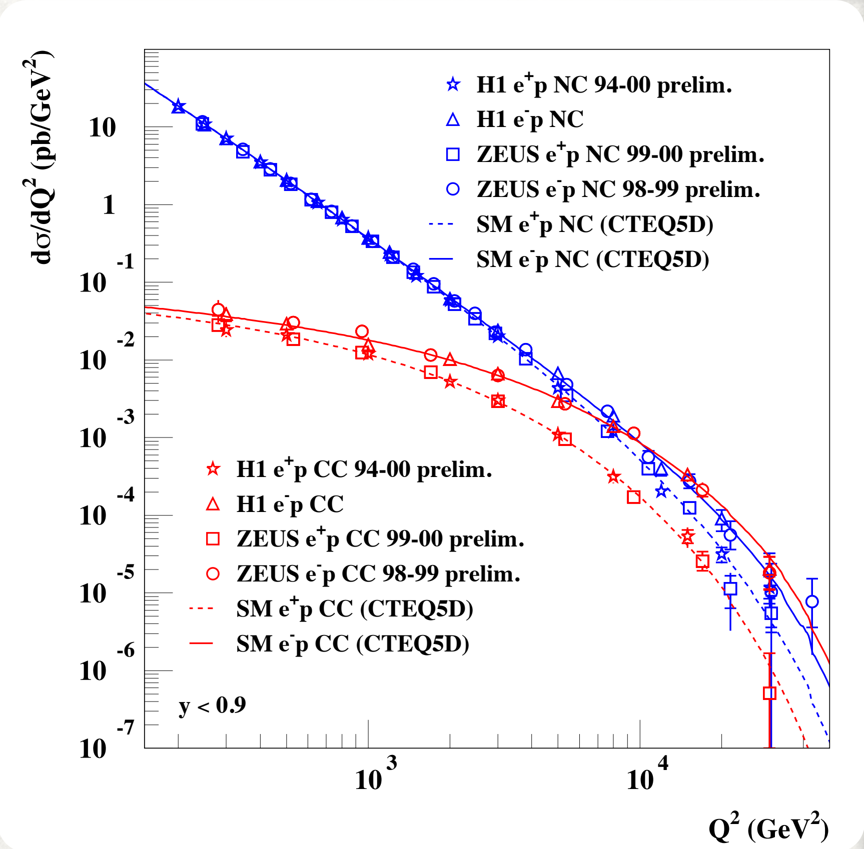




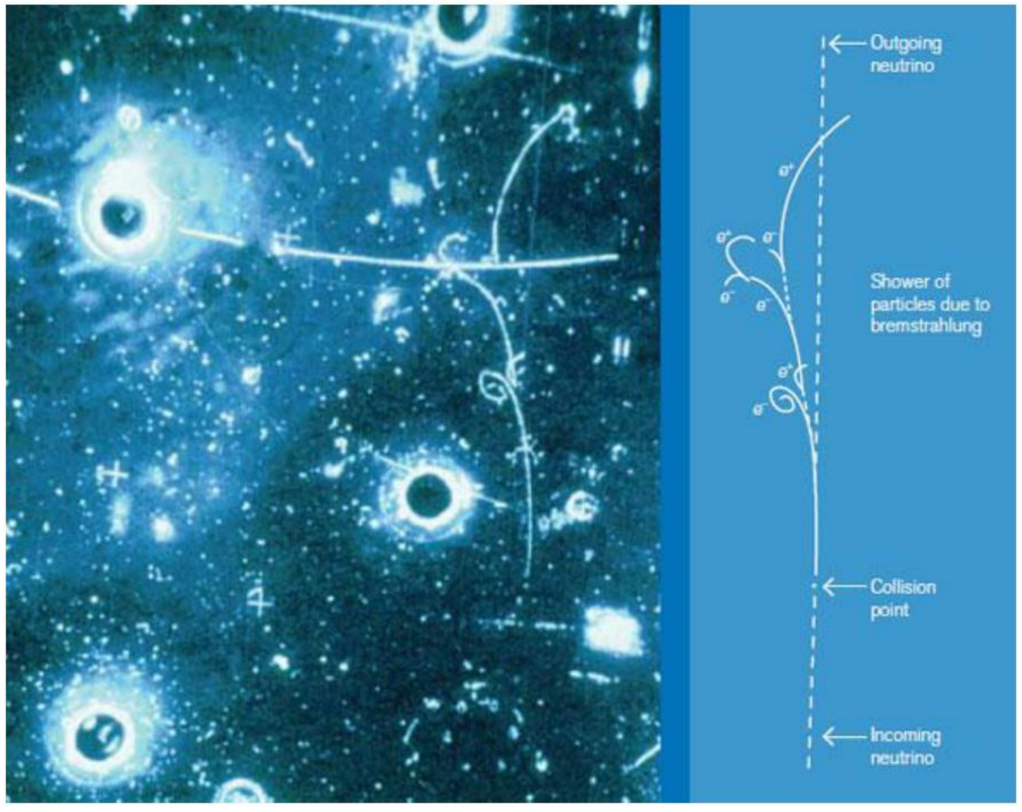
1979 Nobel A. Salam, S. Weinberg, S. Glashow

$$e^{\pm}p \xrightarrow{\gamma, Z} e^{\pm}X$$

$$e^{\pm}p \xrightarrow{W^{\pm}} \nu(\bar{\nu})X$$



Gargamelle bubble chamber: leptonic neutral current



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fenomenología:

1983 UA1/UA2 (CERN) $(400\,GeV)$

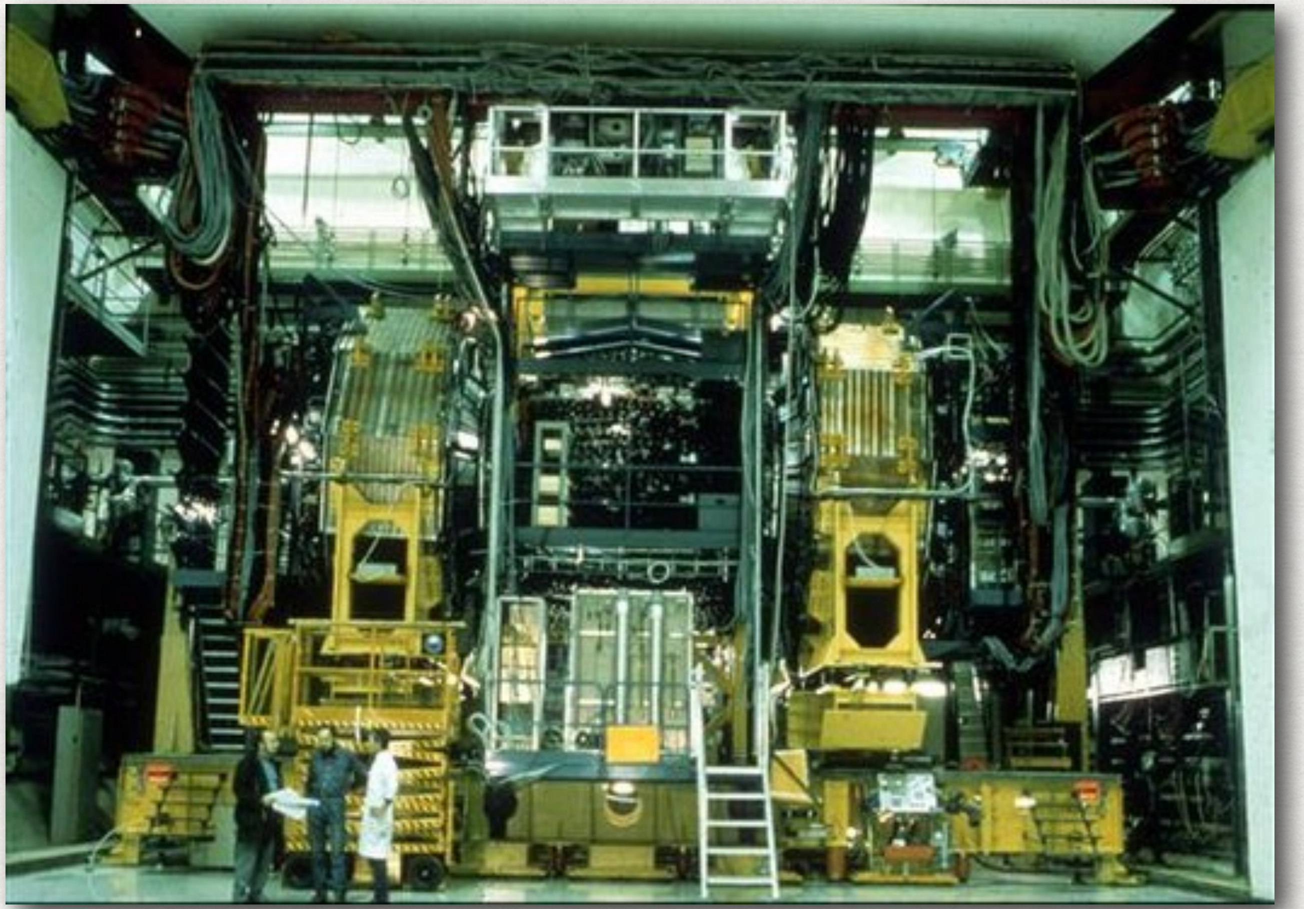
$$p + \overline{p}$$

$$u + \overline{d} \longrightarrow W^+ \longrightarrow e^+ + \nu_e \quad (\mu^+ + \nu_\mu)$$

$$d + \overline{u} \longrightarrow W^- \longrightarrow e^- + \overline{\nu}_e \quad (\mu^- + \overline{\nu}_\mu)$$

$$u + \overline{u} \longrightarrow Z^0 \longrightarrow e^+ + e^- \quad (\mu^+ + \mu^-)$$

$$d + \overline{d} \longrightarrow Z^0 \longrightarrow e^+ + e^- \quad (\mu^+ + \mu^-)$$



1989 LEP (CERN) $(100\,GeV)$

$$e^- + e^+ \longrightarrow Z^0 \longrightarrow \mu^+\mu^-$$

1995 LEP2 (CERN) $(200\,GeV)$

$$e^- + e^+ \longrightarrow Z^0$$

$$\longrightarrow W^+W^- \longrightarrow e^+\nu_e\, e^-\overline{\nu}_e$$

$$e^- + e^+ \longrightarrow A$$

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ruptura espontanea (1960):

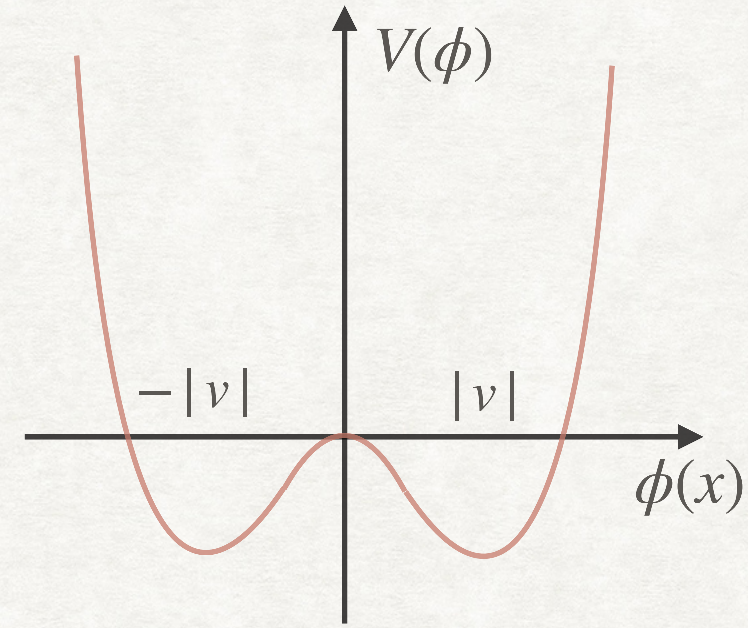
cómo puede ser que $SU(2)_L \times U(1)$ sea simetría, y los mediadores E-W tengan masas?

masa: concepto "heredado" de Newton!

$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

si $\mu^2 > 0$ ~KG con $m = \mu$ $\quad V(\phi) \sim \frac{1}{4}\lambda\phi^4$

si $\mu^2 < 0$ ~KG con $m = 0$ $\quad V(\phi) \sim \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$



$$\phi(x) \longrightarrow -\phi(x) \qquad v \equiv \pm\sqrt{\frac{-\mu^2}{\lambda}}$$

$$\phi(x) = v + \eta(x)$$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \lambda v^2\eta^2 + \lambda v\eta^3 - \frac{1}{2}\lambda\eta^2 + cte$$

$$= \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}\underbrace{(-2\mu^2)}_{m_\eta^2 > 0}\eta^2 + \lambda v\eta^3 - \frac{1}{2}\lambda\eta^2 + cte$$

ϕ ~KG con $m = 0$ y simetría

η ~KG con $m \neq 0$ y sin simetría

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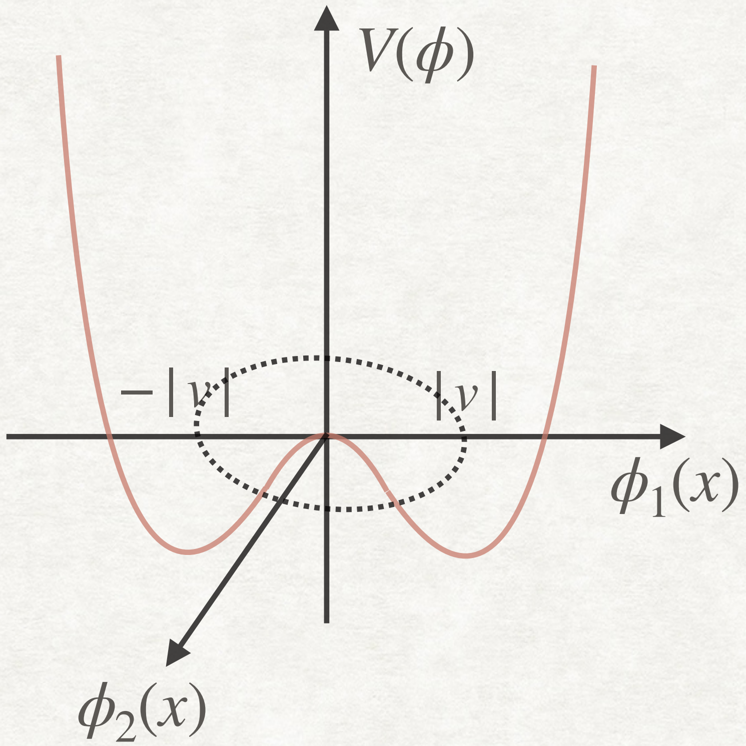
ruptura espontanea (1960):

$$\mathscr{L} = \partial_\mu \phi^* \partial^\mu \phi - \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2$$

$$\phi_1^2(x) + \phi_2^2(x) = v^2 \qquad v^2 = \frac{-\mu^2}{\lambda}$$

$$\phi(x) = \frac{1}{\sqrt{2}}(v + H(x)) = \frac{1}{\sqrt{2}}(v + h(x) + i\rho(x))$$

$$\mathscr{L} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\partial_\mu \rho \partial^\mu \rho - \frac{1}{2}\underbrace{(-2\mu^2)}_{m_h^2 > 0} h^2 + \ldots$$



$$\mathscr{L} = (\partial_\mu + igA_\mu)\phi^*(\partial^\mu - igA^\mu)\phi - \mu^2 \phi^* \phi - \lambda(\phi^*\phi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$\mathscr{L} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\partial_\mu \rho \partial^\mu \rho - \frac{1}{2}\underbrace{(-2\mu^2)}_{m_h^2 > 0} h^2 + \underbrace{\frac{1}{2} g^2 v^2}_{m_A^2 > 0} A_\mu A^\mu + \ldots$$

Y. Nambu

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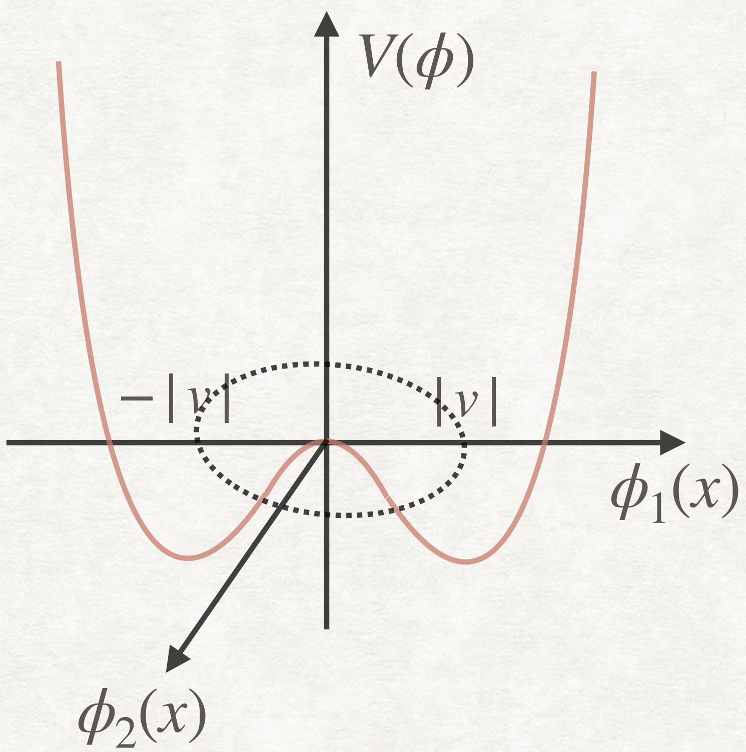
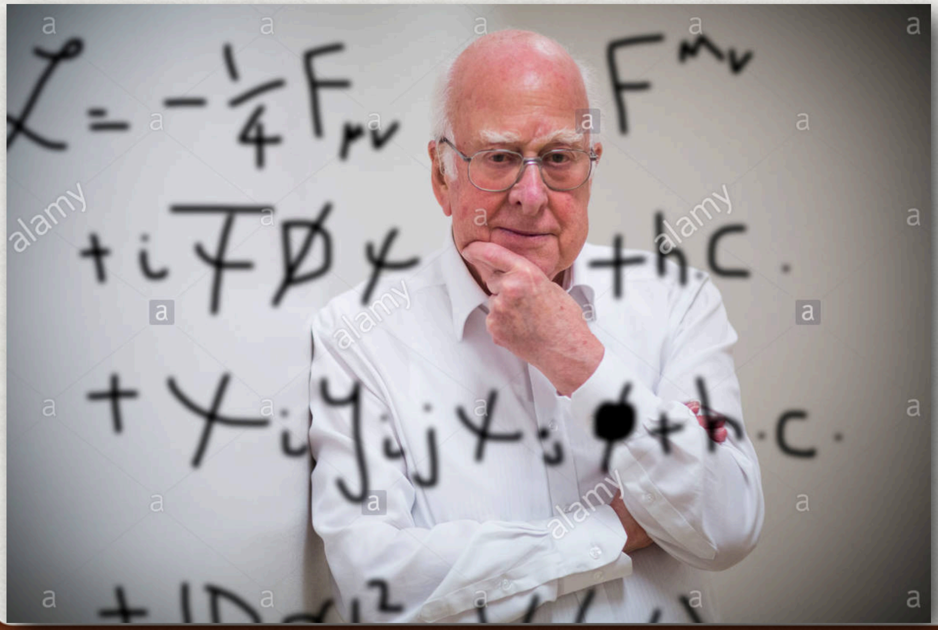
ruptura espontanea (1960):

$$\phi(x) = \frac{1}{\sqrt{2}}(v + h(x) + i\rho(x)) = \frac{1}{\sqrt{2}}(v + h(x))\, e^{i\theta(x)/v}$$

$$\mathscr{L} = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}(-2\mu^2)\, h^2 + \frac{1}{2}g^2 v^2 A_\mu A^\mu +$$

$$+\frac{1}{2}g^2 h^2 A_\mu A^\mu + v g^2 h A_\mu A^\mu - \lambda v h^3 - \frac{1}{4}\lambda h^4 + \dots$$





P. Higgs

Y. Nambu

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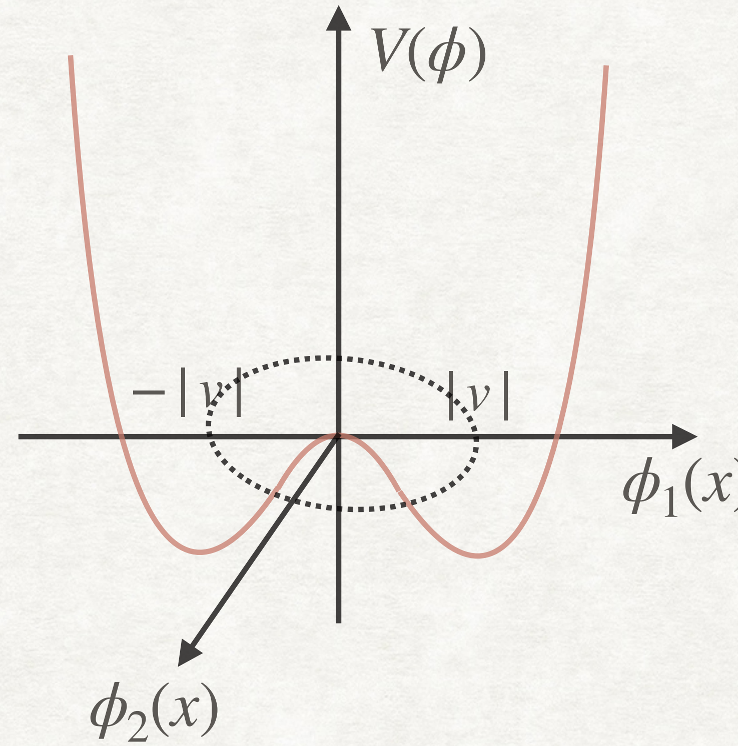
mecanismo de Higgs (1964):

$$\Phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \phi^+ \equiv \tfrac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \quad \phi^0 \equiv \tfrac{1}{\sqrt{2}}(\phi_3 + i\phi_4)$$



$$\mathscr{L} = \partial_\mu \Phi^\dagger \partial^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^2 \qquad \Phi^\dagger\Phi = \frac{-\mu^2}{\lambda}$$

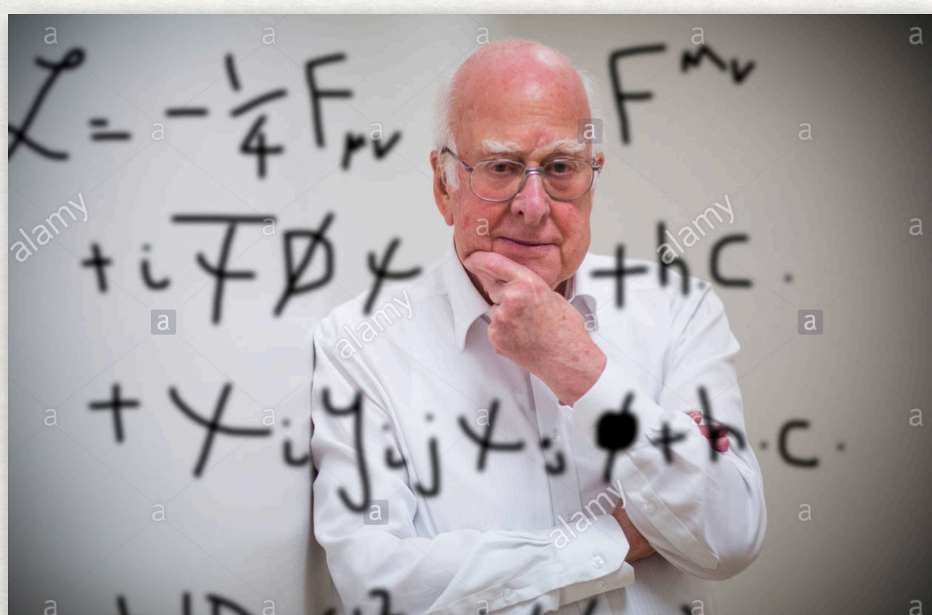
$$\mathscr{L} = (D_\mu \Phi)^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^2$$

$$\Phi(x) = \begin{pmatrix} 0 \\ \dfrac{v + h(x)}{\sqrt{2}} \end{pmatrix} e^{i\theta_i(x)\sigma_i/2}$$

$$(D_\mu \Phi)^\dagger D^\mu \Phi =$$

$$(\partial_\mu \Phi - ig\frac{\sigma_i}{2} W^i_\mu \Phi)^\dagger (\partial^\mu \Phi - ig\frac{\sigma_i}{2} W^\mu_i \Phi)$$

$$\sim \frac{g^2 v^2}{8}[W_1^2 + W_2^2 + W_3^2]$$



P. Higgs

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