

ESTRUCTURA DE LA MATERIA 4

2DO CUATRIMESTRE 2025

CLASE 16

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

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

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

$M_W \neq 0$ $M_{Z^0} \neq 0$ 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:

$$\mathcal{L}_{int}^{QED} \sim q \bar{\Psi}_e \gamma^\mu \Psi_e A_\mu \quad \mathcal{L}_{int}^{U(1)} \sim \frac{g_1}{2} [Y_L^e \bar{e}_L \gamma^\mu e_L + Y_R^e \bar{e}_R \gamma^\mu e_R + Y_L^\nu \bar{\nu}_L \gamma^\mu \nu_L + Y_R^\nu \bar{\nu}_R \gamma^\mu \nu_R] B_\mu$$

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

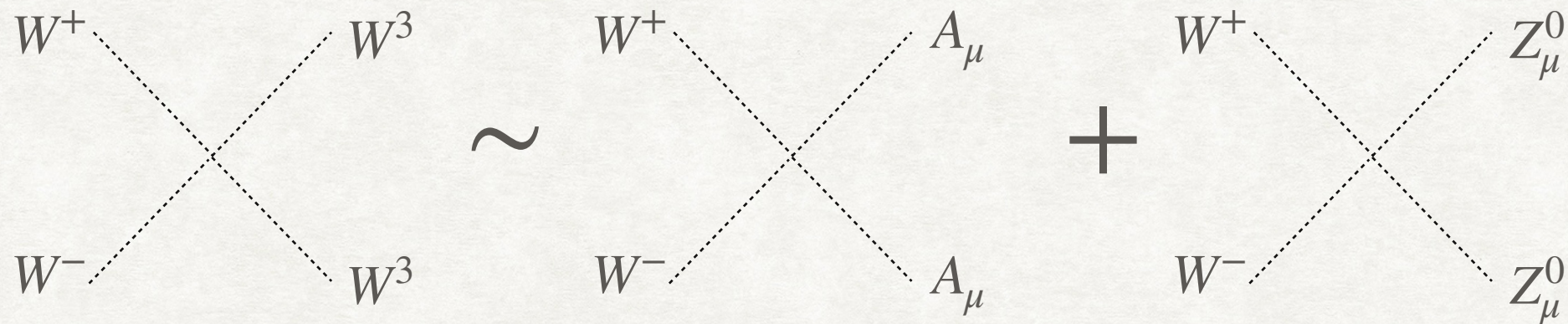
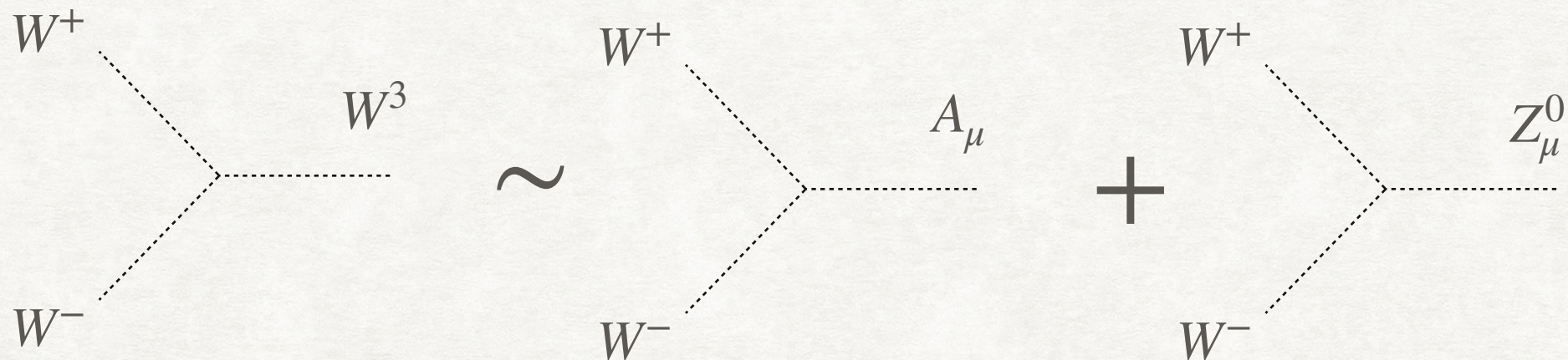
$$W_\mu^\pm \equiv \frac{-1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2) \quad \mathcal{L}_{int}^{SU(2)_L} \sim \frac{g_2}{2} [-\sqrt{2} \bar{\nu}_L \gamma^\mu e_L W_\mu^+ - \sqrt{2} \bar{e}_L \gamma^\mu \nu_L W_\mu^- + \bar{\nu}_L \gamma^\mu \nu_L W_\mu^3 + \bar{e}_L \gamma^\mu e_L W_\mu^3]$$

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

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

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Teoría electro-débil:



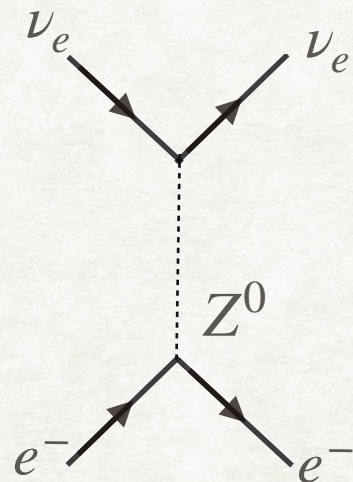
$$\sum_i W_{\mu\nu}^i W_i^{\mu\nu} = \sum_i \left((\partial_\mu W_\nu^i - \partial_\nu W_\mu^i) + g W_\mu^j W_\nu^k \epsilon_{ijk} \right) \left((\partial^\mu W_i^\nu - \partial^\nu W_i^\mu) + g W_j^\mu W_k^\nu \epsilon_{ijk} \right)$$

$$\epsilon_{1jk} \epsilon_{1rs} = \delta_j^r \delta_k^s - \delta_j^s \delta_k^r$$

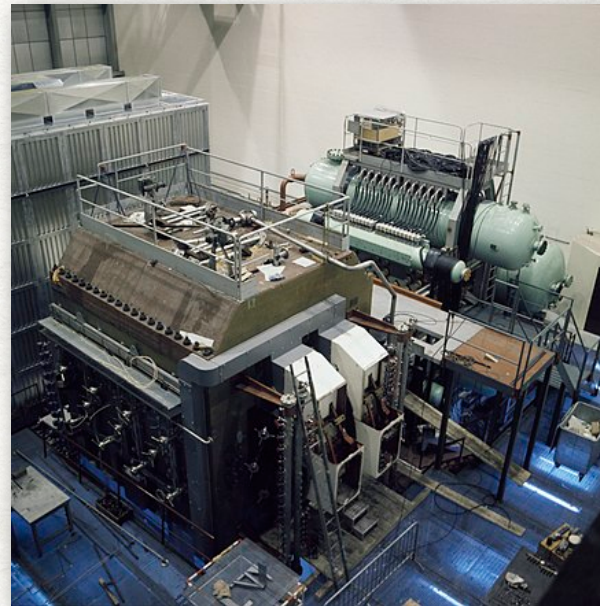
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fenomenología:

1973 Gargamelle (CERN)

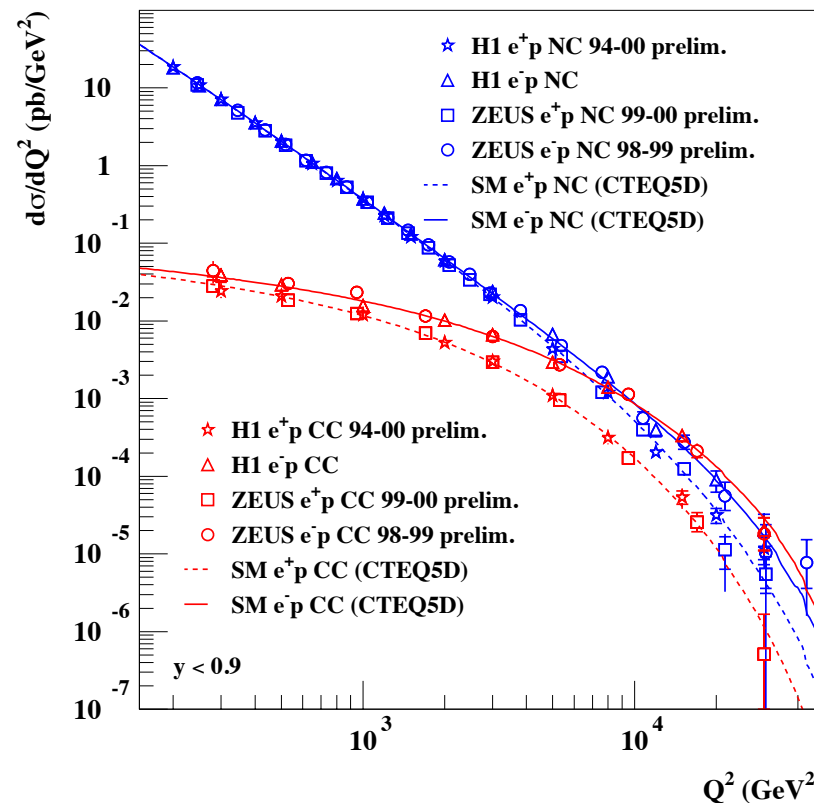


1979 Nobel A. Salam, S. Weinberg, S. Glashow

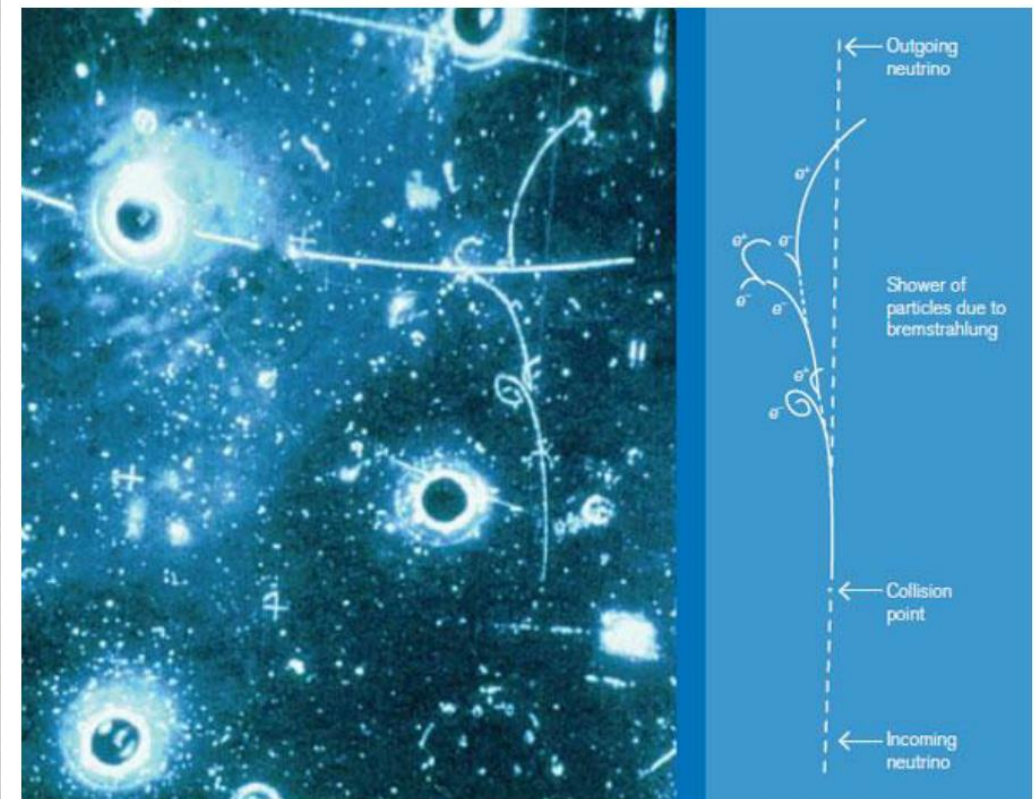


$$e^\pm p \xrightarrow{\gamma, Z} e^\pm X$$

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



Gargamelle bubble chamber: leptonic neutral current



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fenomenología:

1983 UA1/UA2 (CERN) (400 GeV)

$$p + \bar{p}$$

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

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

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

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

1989 LEP (CERN) (100 GeV)

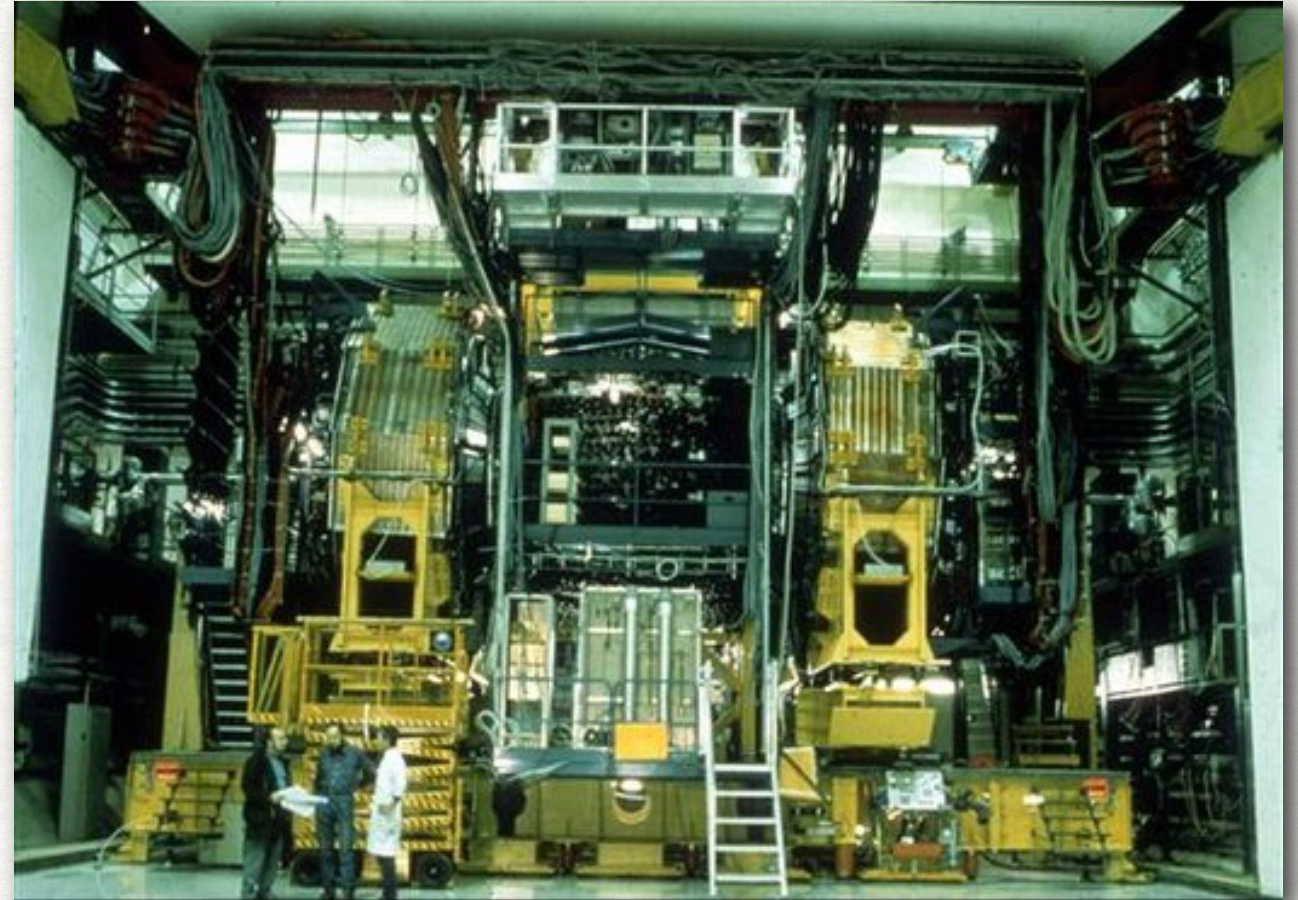
$$e^- + e^+ \longrightarrow Z^0 \longrightarrow \mu^+ \mu^-$$

1995 LEP2 (CERN) (200 GeV)

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

$$\longrightarrow W^+ W^- \longrightarrow e^+ \nu_e \quad e^- \bar{\nu}_e$$

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



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ruptura espontanea (1960):

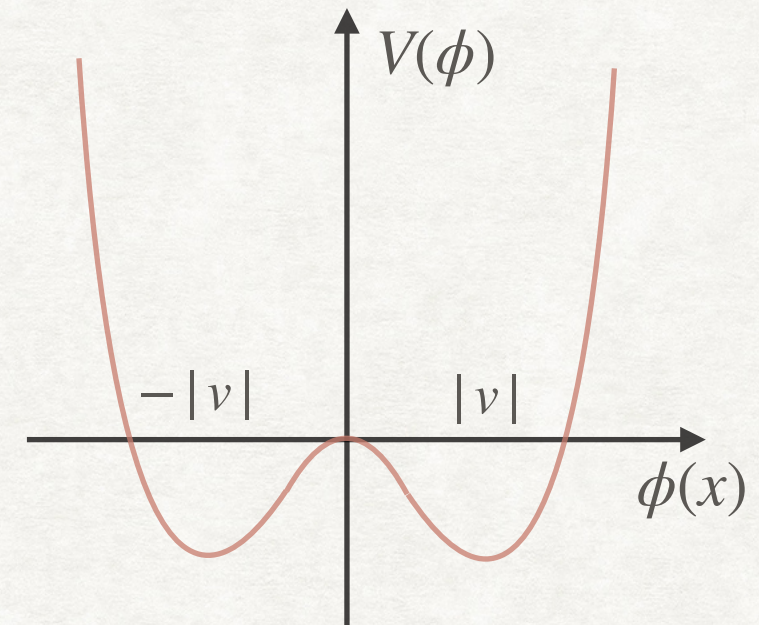
cómo puede ser que $SU(2)_L \times U(1)$ sea simetría, y los mediadores E-W tengan masas?

masa: concepto "heredado" de Newton!

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

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

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



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

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

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

ϕ ~KG con $m = 0$ y simetría

η ~KG con $m \neq 0$ y sin simetría



Y. Nambu

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ruptura espontanea (1960):

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

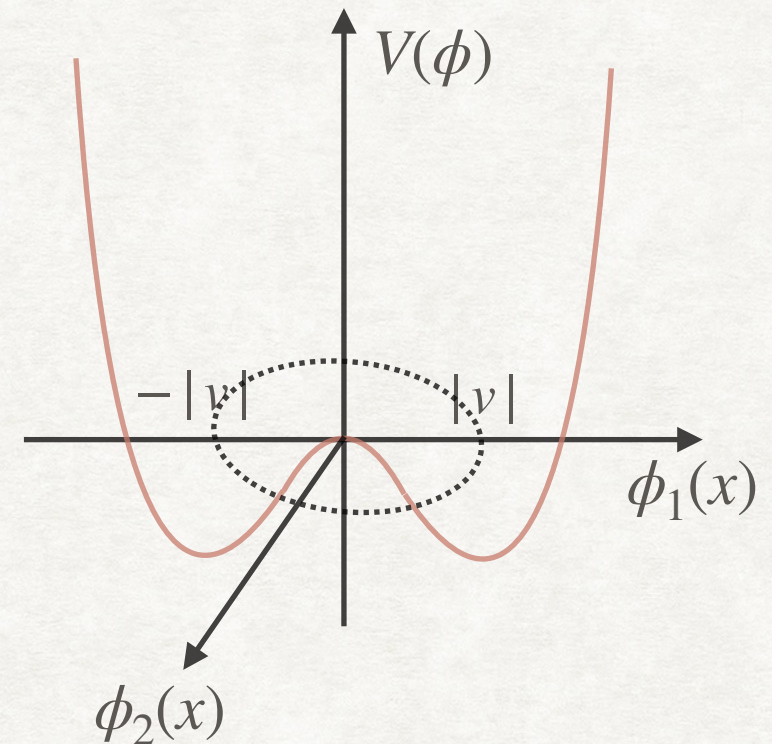
$$\phi_1^2(x) + \phi_2^2(x) = v^2 \quad v^2 = \frac{-\mu^2}{\lambda}$$

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

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

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

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



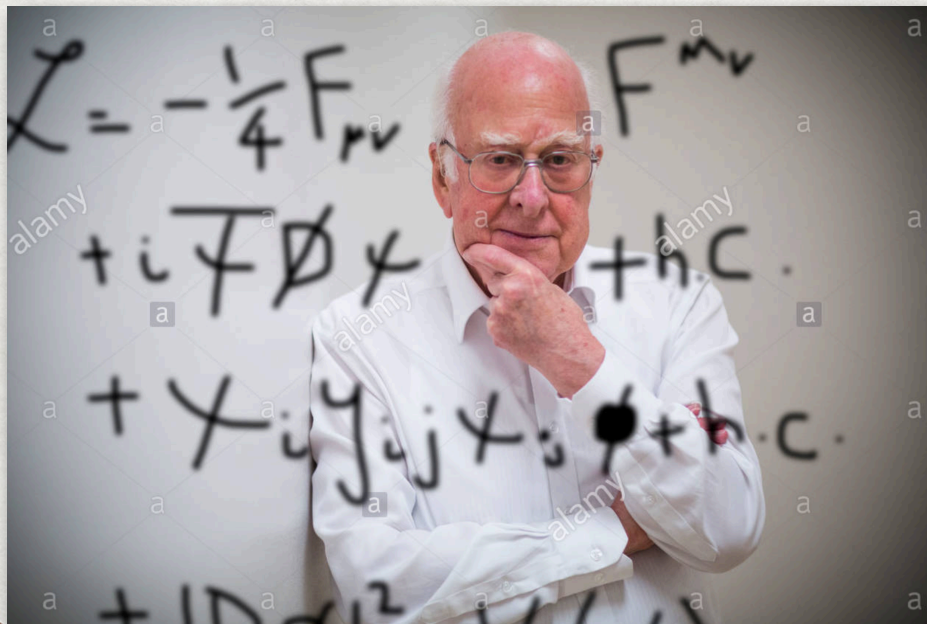
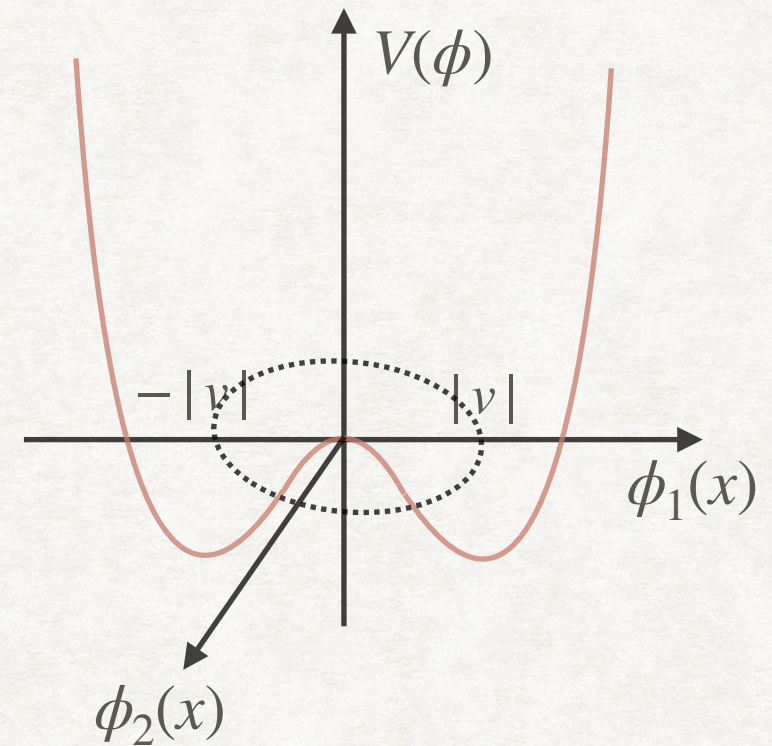
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ruptura espontanea (1960):

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

$$\mathcal{L} = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}(-2\mu^2)h^2 + \frac{1}{2}g^2 v^2 A_\mu A^\mu + \\ + \frac{1}{2}g^2 h^2 A_\mu A^\mu + v g^2 h A_\mu A^\mu - \lambda v h^3 - \frac{1}{4}\lambda h^4 + \dots$$



P. Higgs



Y. Nambu

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mecanismo de Higgs (1964):

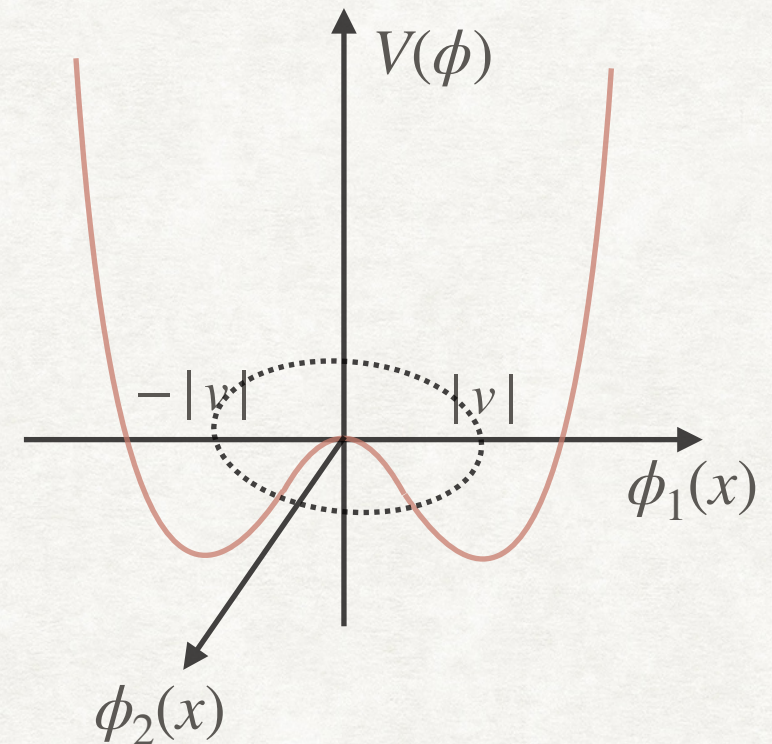
$$\Phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \begin{aligned} \phi^+ &\equiv \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \\ \phi^0 &\equiv \frac{1}{\sqrt{2}}(\phi_3 + i\phi_4) \end{aligned}$$

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

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

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

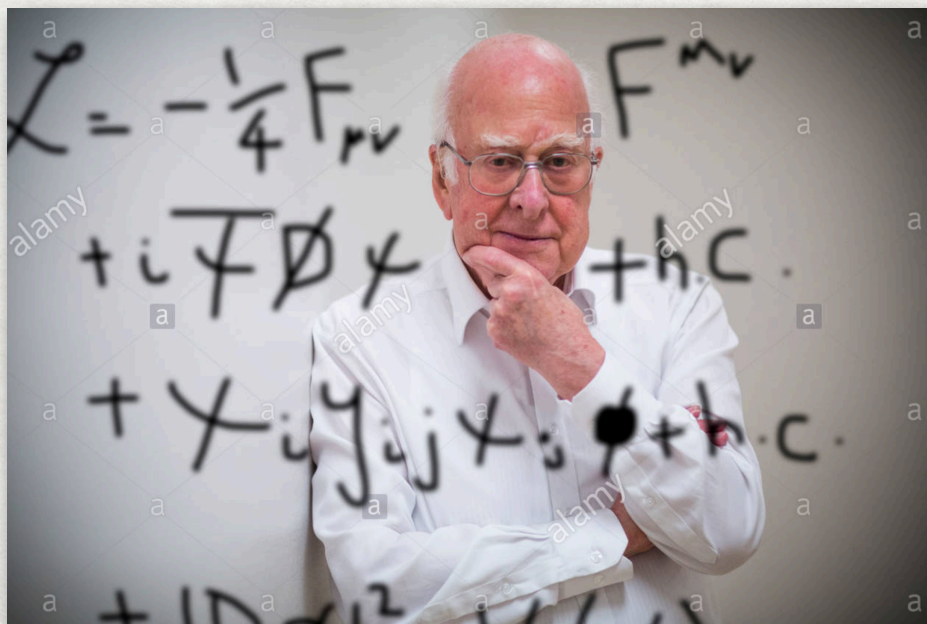
$$\Phi^\dagger \Phi = \frac{-\mu^2}{\lambda}$$



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

$$(\partial_\mu \Phi - ig \frac{\sigma_i}{2} W_\mu^i \Phi)^\dagger (\partial^\mu \Phi - ig \frac{\sigma_i}{2} W_i^\mu \Phi)$$

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



P. Higgs



Y. Nambu