U(1) gauge symmetry

$$\mathcal{L} = \bar{\psi}(x)\,(i\gamma^\mu \partial_\mu - m)\psi(x)$$

$$\psi(x) \to e^{-i\theta}\psi(x) \qquad (1 - i\theta)\psi$$

$$\bar{\psi}(x) \longrightarrow \bar{\psi}(x)\, e^{+i\theta}$$

$$j_\mu = \frac{\partial \mathcal{L}}{\partial\, \partial_\mu \psi}\,\overbrace{i\psi}^{\delta\psi} \qquad j_\mu = \bar{\psi}\gamma_\mu \psi$$

$$\theta \to \theta(x)$$ پیمانه‌ای

$$\mathcal{L} \to \mathcal{L} + j^\mu \partial_\mu \theta$$

$$\partial_\mu \longrightarrow D_\mu = \partial_\mu - ie A_\mu$$ مشتق هموردا

$$\psi(x) \to e^{-i\theta}\psi(x)$$

$$A_\mu \longrightarrow A_\mu - \frac{1}{e}\partial_\mu \theta$$

$$\bar{\psi}\, i\gamma^\mu D_\mu \psi - \bar{\psi} m \psi$$

$$D_\mu \psi \longrightarrow e^{-i\theta} D_\mu \psi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

اتحاد $$[D_\mu, D_\nu]\psi = -ie F_{\mu\nu}\psi$$

$$\cancel{m^2 A_\mu A^\mu}$$

Kinetic term

علت بهتر را پایین می بینیم

$$\mathcal{L}_{QED} = \bar{\psi}(x)\,(i\gamma^\mu D_\mu - m)\psi + \left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right)$$

معادلات اویلر-لاگرانژ ← معادلات ماکسول *

جمله‌ی آخر ۳.۲.۱

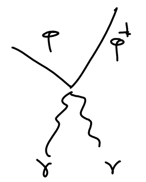
برهمکنش یوکاوا از نوع پیمانه‌ای نیست.

برهمکنش اسکالر

$$(\partial_\mu\varphi)^\dagger\,\partial^\mu\varphi$$

$$\varphi \to e^{-i\theta}\varphi$$

$$\partial^\mu \to D^\mu = \partial^\mu - ieA^\mu$$



$$(D_\mu\varphi)^\dagger D^\mu\varphi = (\partial^\mu\varphi^\dagger + ieA^\mu\varphi^\dagger)(\partial_\mu\varphi - ieA_\mu\varphi) =$$

$$(\partial^\mu\varphi)^\dagger\partial_\mu\varphi + eA^\mu i\left(\varphi^\dagger\partial_\mu\varphi - (\partial_\mu\varphi)^\dagger\varphi\right) + e^2A^\mu A_\mu\varphi^\dagger\varphi$$

حد غیرنسبیتی

$$\psi(p) = \frac{1}{\sqrt{2E_p}}\sum_s\left(a_p^s u^s e^{-ip\cdot x} + a_p^{s\dagger} v\, e^{ip\cdot x}\right)$$

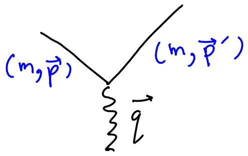
$$u = \begin{bmatrix}\sqrt{p\cdot\sigma}\;\chi \\ \sqrt{p\cdot\bar{\sigma}}\;\chi\end{bmatrix}$$

$$E \simeq m \qquad |\vec{p}| \ll m$$

حد غیرنسبیتی

$$\sqrt{p\cdot\sigma} = \sqrt{E - \vec{p}\cdot\vec{\sigma}} = \sqrt{m}\left(1 - \frac{\vec{\sigma}\cdot\vec{p}}{2m}\right)$$

$$\sqrt{p\cdot\bar{\sigma}} = \sqrt{E + \vec{p}\cdot\vec{\sigma}} = \sqrt{m}\left(1 + \frac{\vec{\sigma}\cdot\vec{p}}{2m}\right)$$



$$\bar u \gamma^0 u = 2m\ \chi'^\dagger \cdot \chi$$

$$\bar u \gamma^i u = \left[\chi'^\dagger\sqrt{p'\cdot\sigma}\quad \chi'^\dagger\sqrt{p'\cdot\bar\sigma}\right]\begin{bmatrix} -\sigma^i & 0 \\ 0 & \sigma^i \end{bmatrix}\begin{bmatrix}\sqrt{p\cdot\sigma}\,\chi \\ \sqrt{p\cdot\bar\sigma}\,\chi\end{bmatrix}$$

$$= m\left[\chi'^\dagger\left(1-\frac{\vec\sigma\cdot\vec p\,'}{2m}\right)\sigma^i\left(1-\frac{\vec\sigma\cdot\vec p}{2m}\right)\chi\right.$$

$$\left. - \chi'^\dagger\left(1+\frac{\vec\sigma\cdot\vec p\,'}{2m}\right)\sigma^i\left(1+\frac{\vec\sigma\cdot\vec p}{2m}\right)\chi\right]$$

$$\vec p\,' = \langle\vec p\rangle + \frac{\vec q}{2}$$

$$\vec p = \langle\vec p\rangle - \frac{\vec q}{2}$$

$$\bar u \gamma^i u = -2m\ \chi'^\dagger\left[\frac{\overbrace{\{\langle\vec p\rangle\cdot\vec\sigma,\ \sigma^i\}}^{2\langle\vec p\rangle^i}}{2m} + \frac{\overbrace{\left[\frac{\vec q\cdot\vec\sigma}{2},\ \sigma^i\right]}^{2i\epsilon^{jik}\frac{q^j\sigma^k}{2}}}{2m}\right]\chi$$

$$\Rightarrow\quad A_i\,\bar u\gamma^i u = -2\vec A\cdot\langle\vec p\rangle\,\chi'^\dagger\chi - \vec B\cdot\chi'^\dagger\vec\sigma\chi$$

$$A_\mu\bar\psi\gamma^\mu\psi = A_0\ \overbrace{\chi'^\dagger\chi}^{1} + \frac{\vec A\cdot\langle\vec p\rangle\,\chi'^\dagger\chi}{m} + \frac{\vec B\ \overbrace{\chi'^\dagger\vec\sigma\chi}^{2\vec S}}{2m}$$

بستگی به اسپین ندارد

$\chi' = \chi$

تجدید خاطرات

فصل ۵.۳ ساکورایی (انرزیان)

$$A = -\frac{1}{2}\left(By\,\hat x - Bx\,\hat y\right)$$

از موج تخت نباید استفاده کنیم

$$\vec A\cdot\vec p = |\vec B|\left(-\frac{y}{2}p_x + \frac{xp_y}{2}\right)$$

$$\vec A\cdot\vec p = \frac{|\vec B|\,L_z}{2}$$

از بسته موج باید استفاده کنیم

$$V = -e\,\bar\psi\gamma^\mu\psi A_\mu = \frac{-eB}{2m}\left(L+2S\right)$$

$g=2 \leftarrow$ tree level

$$\mu = \frac{g\,qB}{2m}\vec S$$

ذره‌ی باردار با اسپین $\frac{1}{2}$:

$$\frac{eB}{2m_e} = g_B$$ مگنتون بور

$$\frac{eB}{2m_p} = g_N$$ Nuclear magneton

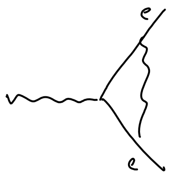
PDG 2006

درمورد الکترون $\mu_e = 1.00115965\,21859 \pm 0.0\ldots\ldots\ 38\ \mu_B$

PDG 2008

Magnetic moment anomaly

$$\frac{g-2}{2} = (1159.65\,21\,811 \pm 0.0000007) \times 10^{-6}$$



از جمله مهمترین مشاهده پذیری ذرات میون

$$\frac{g-2}{2} = (11\,659\,208 \pm 6) \times 10^{-10}$$

OLD SM $\longrightarrow$ برای $\mu_\nu = 0$

$$\mu_\nu < 0.74 \times 10^{-10}\ \mu_B$$

$\mu_{\pi^\pm}$ μ_{π^0}

Magnetic dipole

Proton

$$\mu = 2.792847351 \pm 0.000000028\ \mu_N$$

neutron

$$\mu = -1.9130427 \pm 0.0000005\ \mu_N$$

anomalous

$d \longrightarrow 0$ درمورد همه ی این ذرات

$$\vec{S} \xrightarrow{T} -\vec{S}$$

$$\vec{S} \xrightarrow{T} -\vec{S}$$

$$\vec{B} \xrightarrow{T} -\vec{B}$$

$$\vec{E} \xrightarrow{T} +\vec{E}$$

$$d\, S\cdot\vec{E} + \mu\, \vec{S}\cdot\vec{B}$$

$$\Big\downarrow T$$

$$-d\,\vec{S}\cdot\vec{E} + \mu\,\vec{S}\cdot\vec{B}$$

$d_e < 1.4 \times 10^{-27}\ e\,cm$ ← PDG

$d_\mu < 1.9 \times 10^{-19}\ e\,cm$ ← arXiv: 0811.1207

$e + \gamma \longrightarrow e\gamma$	برهمکنش کامپتون
$e^- e^- \longrightarrow e^- e^-$	Moller scattering
$e^- e^+ \longrightarrow \gamma\gamma$	pair annihilation
$e^- e^+ \longrightarrow e^- e^+$	BHABHA scattering

$$\mathcal{L}(\varphi, \partial_\mu \varphi)$$

$$\varphi_a \longrightarrow \varphi_a + \delta\varphi_a$$

$$\delta\mathcal{L} = \partial_\mu K^\mu = \frac{\partial\mathcal{L}}{\partial\varphi_a}\delta\varphi_a + \frac{\partial\mathcal{L}}{\partial(\partial_\mu\varphi_a)}\delta\partial_\mu\varphi_a$$

$$= \left(\frac{\partial\mathcal{L}}{\partial\varphi_a} - \partial_\mu\frac{\partial\mathcal{L}}{\partial\partial_\mu\varphi_a}\right)\delta\varphi_a + \partial_\mu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\varphi_a)}\delta\varphi_a\right) =$$

$$\partial_\mu\left(\frac{\partial\mathcal{L}}{\partial\partial_\mu\varphi_a}\delta\varphi_a\right)$$

جریان نوتر $\quad J^\mu = \dfrac{\partial\mathcal{L}}{\partial\partial_\mu\varphi_a}\delta\varphi_a - K^\mu$

در بیشتر مواردی که در فیزیک ذرات ما سروکار داریم $K=0$ یعنی

تحت تبدیل نه تنها کنش ($\int d^4x\, \mathcal{L}$) بلکه چگالی لاگرانژی

(یعنی $\mathcal{L}$) ناورداست.

تانسور انرژی - تکانه که بیشتر در کیهان‌شناسی با آن سروکار داریم

[illegible]

یک اشتباه است.

تقارن انتقال فضا-زمان

$$x^\mu \longrightarrow x^\mu + a^\mu \qquad \varphi_a(x) \longrightarrow \varphi_a(x) + a^\mu \partial_\mu \varphi_a(x)$$

$$\mathcal{L} \to \mathcal{L} + a^\mu \partial_\mu \mathcal{L} \qquad T^\mu{}_\nu = \frac{\partial \mathcal{L}}{\partial \partial_\mu \varphi} \partial_\nu \varphi - \mathcal{L}\, \delta^\mu{}_\nu$$

SU(n)

$$\varphi_a \longrightarrow \varphi_a + \delta \varphi_a$$

$$\delta \varphi_a = -i\theta^i T^i_{ab} \varphi_b \qquad \varphi_a \longrightarrow \varphi'_a = e^{-i\theta^i T^i_{ab}} \varphi_b$$

$$a, b = 1 \dots n$$

$$j^{i\mu}(x) \equiv -i \frac{\partial \mathcal{L}}{\partial \partial_\mu \varphi_a} T^i_{ab} \varphi_b$$

$$Q^i(t) \equiv \int d^3x \; j^{i0}(\vec{x}, t)$$

Canonical quantization

$$\pi_a = \frac{\partial \mathcal{L}}{\partial(\partial_0 \varphi_a)}$$

$$[\varphi_a(\vec{x}, t), \varphi_b(\vec{x}, t)] = [\pi_a(\vec{x}, t), \pi_b(\vec{x}, t)] = 0$$

$$[\varphi_a(\vec{x}, t), \pi_b(\vec{x}, t)] = i\delta_{ab}\, \delta^3(\vec{x} - \vec{y})$$

اشتباه تایپی کتاب رابطه ۳.۱۴

کواسمی

$$\partial_\mu j^{i\nu} = i[P_\mu, j^{i\nu}]$$

عملگر چهار-تکانه

$$\frac{dQ^i}{dt} = i[H, Q^i] = 0$$

$$[Q^i, Q^j] = i f_{ijk} Q^k \qquad *$$

$$[Q^i, \varphi] = -T^i \varphi \quad *$$

$$\varphi \longrightarrow \varphi' = e^{i\theta^i Q^i} \varphi \, e^{-i\theta^i Q^i} = e^{-i\theta^i T^i} \varphi$$

Yang-Mills تئوری پیمانه‌ای

SU(2)

Yang Mills 1954

$$U(1) \longrightarrow SU(2)$$

ایزواسپین سرتاسری است.

$$\psi = \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix} \qquad \psi \to \psi'(x) = U\,\psi(x)$$

$$U = e^{-ig \frac{\tau^i}{2} \theta^i(x)}$$

$$\tau^i = \sigma^i \qquad \tau^1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad \tau^2 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad \tau^3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

ایده‌ی اولیه Yang-Mills

یَنگ و میلز برای طرح کردن ایده‌ی اولیه‌ی خود از دوتایی $\begin{pmatrix} p \\ n \end{pmatrix}$ استفاده کرده بودند

$$D_\mu = \partial_\mu - ig\vec{A}_\mu$$

$$\vec{A}_\mu = \sum_{i=1}^{3} \frac{\tau^i}{2} A_\mu^i = \frac{\vec{\tau}}{2} \cdot \vec{A}_\mu$$

مشابه U(1) می‌خواهیم داشته باشیم

$$D_\mu \psi \longrightarrow (D_\mu \psi)' = D_\mu' \psi' = U (D_\mu \psi)$$

در این صورت $\bar{\psi} D_\mu \gamma^\mu \psi$ ناوردا خواهد ماند.

آیا ترتیب مهم است؟ $D_\mu \gamma^\mu \overset{?}{=} \gamma^\mu D_\mu$

$$(D_\mu \psi)' = D'_\mu U \psi = U (D_\mu \psi)$$

$$\Downarrow$$

$$D'_\mu = U D_\mu U^{-1}$$

$$\downarrow$$

$$\vec{A}'_\mu = U \vec{A}_\mu U^{-1} - \frac{i}{g} (\partial_\mu U) U^{-1}$$

تبدیل‌های بی‌نهایت کوچک

$$U = 1 - i\theta + \mathcal{O}(\theta^2)$$

$$U^{-1} = 1 + i\theta + \mathcal{O}(\theta^2)$$

$$\theta = \sum_{i=1}^{3} \frac{\tau^i}{2} \theta^i = \frac{\vec{\tau}}{2} \cdot \vec{\theta}$$

$$\vec{A}'_\mu = \vec{A}_\mu - i [\theta , \vec{A}_\mu] - \frac{\partial_\mu \theta}{g}$$

$$\delta A^i_\mu = \varepsilon_{ijk} \theta^j A^k_\mu - \frac{\partial_\mu \theta^i}{g}$$

$$[D_\mu , D_\nu] \psi = -ig \vec{F}_{\mu\nu} \psi$$

$$\vec{F}_{\mu\nu} = \sum_{i=1}^{3} \frac{\tau^i}{2} F^i_{\mu\nu} = \frac{\vec{\tau}}{2} \cdot \vec{F}_{\mu\nu}$$

$$F^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu + g \varepsilon_{ijk} A^j_\mu A^k_\nu$$

$$\vec{F}'_{\mu\nu} = U \vec{F}_{\mu\nu} U^{-1}$$

$$\mathrm{Tr}[\vec{F}'_{\mu\nu} \cdot \vec{F}^{\mu\nu\,\prime}] = \mathrm{Tr}[\vec{F}_{\mu\nu} \cdot \vec{F}^{\mu\nu}]$$

$$-\frac{1}{2} \mathrm{Tr}[\vec{F}_{\mu\nu} \cdot \vec{F}^{\mu\nu}] = -\frac{1}{2} \sum_{i,j=1}^{3} \mathrm{Tr}\left[\frac{\tau^i}{2} F^i_{\mu\nu} \frac{\tau^j}{2} F^{j\mu\nu}\right]$$

$$= -\frac{1}{4} F^i_{\mu\nu} F^{i\mu\nu}$$

$$\mathcal{L} = \mathcal{L}_F + \mathcal{L}_G$$

$$\mathcal{L}_F = \bar{\Psi}(i\not{\partial} - m)\Psi$$

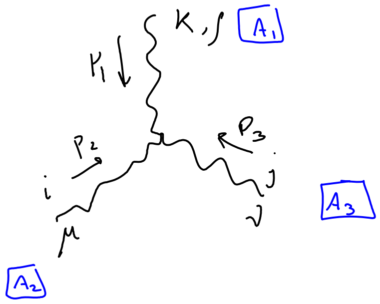
$$\mathcal{L}_G = \underbrace{-}_{\text{علامت منفی}} \frac{1}{2} \mathrm{Tr}\left[\vec{F}_{\mu\nu} \cdot \vec{F}^{\mu\nu}\right]$$

$$F_{0i} = -E A^i \qquad F^{0i} = E A^i$$

$$\cancel{m A^i_\mu A^{i\mu}}$$

$$\mathcal{L}_G = -\frac{1}{2} \partial_\mu A^i_\nu \left(\partial^\mu A^{i\nu} - \partial^\nu A^{i\mu} \right)$$

$$- g\, \varepsilon_{ijk} A^i_\mu A^j_\nu \partial^\mu A^{k\nu} - \frac{g^2}{4} \varepsilon_{ijk} \varepsilon_{ilm} A^j_\mu A^k_\nu A^{l\mu} A^{m\nu}$$



$*$

$$f_{i_1 j_1 k_1} A^{i_1}_{\mu_1} A^{j_1}_{\nu_1} \partial^{\mu_1} A^{k_1 \nu_1} \mid A_{1\rho,k} A_{2\mu,i} A_{3\nu,j} \rangle$$

$$= f_{i_1 j_1 k_1} A^{i_1}_{\mu_1} A^{j_1}_{\nu_1} \partial^{\mu_1} A^{k_1\nu_1} \mid A_{1\rho,k} A_{2\mu,i} A_{3\nu,j} \rangle$$

$$+ \begin{pmatrix} A_1 \leftrightarrow A_3 \\ P_3 \longleftrightarrow P_1 \\ k \leftrightarrow j \end{pmatrix} + \begin{pmatrix} A_2 \longleftrightarrow A_3 \\ P_3 \longleftrightarrow P_2 \\ j \leftrightarrow i \end{pmatrix}$$

$$= i\Big[P_3 \cdot A_1^k \; A_2^i \cdot A_3^j \quad f_{kij}$$

$$+ P_3 \cdot A_2^i \; A_1^k \cdot A_3^j \quad f_{ikj}$$

$$+ P_1 \cdot A_3^j \; A_2^i \cdot A_1^k \quad f_{jik}$$

$$+ P_1 \cdot A_2^i \; A_1^j \cdot A_3^k \quad f_{ijk}$$

$$\cdot \; D \cdot A^k \quad A^j \cdot A^i \quad f_{\cdot\cdot +}$$

$$+ P_2 \cdot A_1^k \quad A_3^j \cdot A_2^i \quad f_{kji} +$$
$$P_2 \cdot A_3^j \quad A_1^k \cdot A_2^i \quad f_{jki} \Big] = K$$

$$V = g f_{ijk} A_\mu^i A_\nu^j \partial^\mu A^{k\nu}$$

رأس $\quad -iV = gK$

فرقی بین چپ-دست و راست-دست نمی‌گذارد.

جرم A_μ^i نداریم.

$$\mathcal{L} = (\partial_\mu \varphi)^\dagger \partial^\mu \varphi - V(\varphi^* \varphi)$$

$$\varphi = \frac{\varphi_1 + i\varphi_2}{\sqrt{2}} \qquad \varphi^* = \frac{\varphi_1 - i\varphi_2}{\sqrt{2}}$$

$$V(\varphi^*\varphi) = m^2 \varphi^*\varphi + \lambda(\varphi^*\varphi)^2$$

$\lambda > 0 \rightarrow$ Unbounded from below

$$\langle 0|\varphi_1|0\rangle = \varphi_{01} \qquad \langle 0|\varphi_2|0\rangle = \varphi_{02}$$

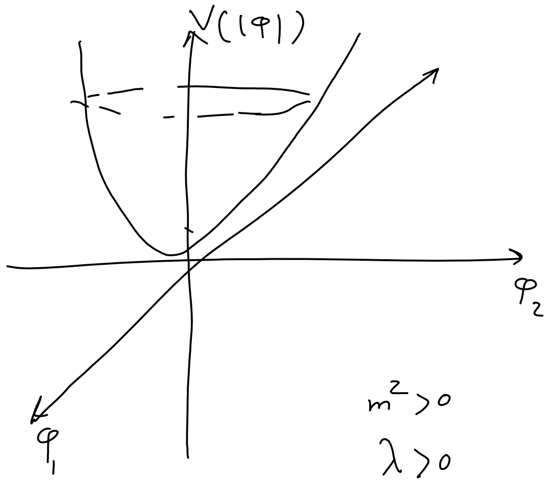
$$V(\varphi_1, \varphi_2) = V(\varphi_{01}, \varphi_{02}) + \sum_{a=1,2} \left(\frac{\partial V}{\partial \varphi_a}\right)_0 (\varphi_a - \varphi_{0a})$$
$$+ \frac{1}{2} \sum_{a,b=1,2} \left(\frac{\partial^2 V}{\partial \varphi_a \partial \varphi_b}\right) (\varphi_a - \varphi_{0a})(\varphi_b - \varphi_{0b}) + \cdots$$

V در $\langle \varphi \rangle = (\varphi_{01}, \varphi_{02})$ کمینه است یعنی جملهٔ دوم صفر می‌شود.

$$m_{ab}^2 = \left(\frac{\partial^2 V}{\partial \varphi_a \partial \varphi_b}\right)_0$$

Wigner phase

فاز ویگنر



$m^2 > 0$

$\lambda > 0$

$$\left(\frac{\partial V}{\partial \varphi_1}\right)_0 = m^2 \varphi_{01} + \lambda \varphi_{01} \left(\varphi_{01}^2 + \varphi_{02}^2 \right) = 0$$

$$\left(\frac{\partial V}{\partial \varphi_2}\right)_0 = m^2 \varphi_{02} + \lambda \varphi_{02} \left(\varphi_{01}^2 + \varphi_{02}^2 \right) = 0$$

$$\varphi_{01} = \varphi_{02} = 0$$

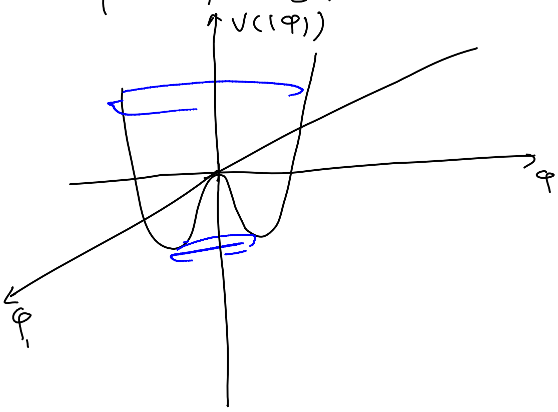
$$m_{ab}^2 = \begin{bmatrix} m^2 & 0 \\ 0 & m^2 \end{bmatrix}$$

Nambu-Goldstone phase

فاز نمبو- گلدستون

$$V(\varphi_1^2 + \varphi_2^2) = -\frac{\mu^2}{2} (\varphi_1^2 + \varphi_2^2) +$$

$$\frac{\lambda}{4} (\varphi_1^2 + \varphi_2^2)^2$$



$$\left(\frac{\partial V}{\partial \varphi_1}\right)_0 = -\mu^2 \varphi_{01} + \lambda \varphi_{01}(\varphi_{01}^2 + \varphi_{02}^2) = 0$$

$$\left(\frac{\partial V}{\partial \varphi_2}\right)_0 = -\mu^2 \varphi_{02} + \lambda \varphi_{02}(\varphi_{01}^2 + \varphi_{02}^2) = 0$$

$$\varphi_{01}^2 + \varphi_{02}^2 = v^2 = \frac{\mu^2}{\lambda}$$

$$\frac{\partial^2 V}{\partial \varphi_1^2} = (-\mu^2 + \lambda(\varphi_1^2 + \varphi_2^2)) + 2\lambda \varphi_1^2$$

$$\frac{\partial^2 V}{\partial \varphi_2^2} = (-\mu^2 + \lambda(\varphi_1^2 + \varphi_2^2)) + 2\lambda \varphi_2^2$$

$$\frac{\partial^2 V}{\partial \varphi_1 \partial \varphi_2} = 2\lambda \varphi_1 \varphi_2$$

$$m_{ab}^2 = \begin{bmatrix} 2\lambda v^2 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\varphi' = \varphi_1 - v$$

$$\varphi'_2 = \varphi_2$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \varphi'_1)^2 + \frac{1}{2}(\partial_\mu \varphi'_2)^2 - \frac{(2\lambda v^2)}{2}\varphi_1'^2$$

$$+ \lambda v \varphi'_1(\varphi_1'^2 + \varphi_2'^2) - \frac{\lambda}{4}(\varphi_1'^2 + \varphi_2'^2)^2$$

تقارن پنهان شده

$2\lambda v^2 = \varphi'_1 = \varphi_1 - v$ جرم

$0 = \varphi'_2$ جرم

$$\varphi = \frac{\rho}{\sqrt{2}} e^{i\theta/v}$$

$$\partial_\mu \varphi = \frac{1}{\sqrt{2}} e^{i\frac{\theta}{v}} \left(\partial_\mu \rho + \frac{i\rho}{v} \partial_\mu \theta \right)$$

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \rho)^2 + \frac{1}{2v^2} \rho^2 (\partial_\mu \theta)^2 - V(\rho^2)$$

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

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \eta)^2 + \frac{1}{2} (\partial_\mu \theta)^2 + \frac{\eta}{v} (\partial_\mu \theta)^2 + \frac{\eta^2}{2v^2} (\partial_\mu \theta)^2$$

$$- V(\rho^2)$$

$$V(\rho^2) = \frac{1}{2} (3\mu^2)\, \eta^2 + \lambda v \eta^3 + \frac{\lambda}{4} \eta^4 - \frac{1}{2} \mu^2 v^2$$

$$m_\eta = \sqrt{2\mu^2}$$

تعمیم به مدل SU(2)

$$\varphi = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}$$