Electroweak precision data
۲۰۱۰/۱۱/۲۵
۱۱:۳۷ ق.ظ

SM $\leftarrow$ تئوری پیمانه‌ای بازبهنجارش پذیر

tree level
- $\rightarrow$ neutral current
- $\rightarrow$ m_{Z^0} و $m_{W^\pm}$
- $\rightarrow$ A_{FB} $\quad e^+e^- \rightarrow f\bar{f}$

radiative correction

LEP CDF

Gauge Sector

3 bare parameters $\begin{cases} g \\ g' \\ \left(\frac{v}{\sqrt{2}}\right) \end{cases}$

$$\begin{cases} m_Z = 91.150(30) \text{ GeV (from LEP, SLC)} \\ G_F = 1.16637(2)\times 10^{-5} \text{ GeV}^{-2} \text{ (from } \mu \to e\,\nu_\mu \bar{\nu}_e) \\ \alpha = 137.0359895(61)^{-1} \text{ (from } g\text{-}2 \text{ of } e) \end{cases}$$

$$M_Z(g, g', v; m_t, m_H, \dots)$$

$$G_F(g, g'; m_t, m_H, \dots)$$

$$\alpha(g, g', v; m_t, m_H, \dots)$$

$$g = \varphi(M_Z, G_F, \alpha \dots)$$

$$\rightarrow f(g, g', v; m_t, m_H, \dots) = \hat{f}(M_Z, G_F, \alpha \dots$$

در بعد ۴ $\swarrow$ تئوری بازبهنجارش پذیر

marginal $\quad$ بعد $=4$ $\quad \lambda\varphi^4$ و $D_\mu\varphi D^\mu\varphi$

relevant $\quad$ بعد <4 $\quad m^2\varphi^2$, $a\varphi^3$

irrelevant   بعد >4

UV divergence Λ^2 , $\log \frac{\Lambda^2}{\mu^2}$

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

finite quantum correction

irrelevant operators $\leftarrow$ finite

$\left.\begin{array}{l} t \\ H \\ \text{unknown particles} \end{array}\right\}$ gauge boson self-energies
$b\bar{b}Z$ vertex

درحالت کلی

heavy particle M $\longrightarrow$ سهم به اپراتورهای irrelevant $\sim \frac{1}{M}$

decoupling

اما نه همیشه

Non-decoupling

Oblique parameters

$$\underbrace{S \quad T \quad U}$$

$\downarrow$

m_t , m_H , new heavy particles

Peskin & Takeuchi, 1990

$\downarrow$

Te~~chni~~color

Decoupling & Non-decoupling

Gaillard & Lee, 1974

$K^0 , \bar{K}^0 \longrightarrow$ c-quark

$$\frac{i}{k^2 - M^2} \longrightarrow \frac{1}{M^2}$$

tree level

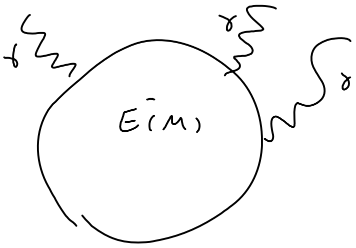
loop ??

نظریه‌ی پیمانه‌ای بدون شکست خودبه‌خود تقارن با بقای پاریته

SSB

QCD یا QED

Appelquist & Carrazone, 1975



$E^-(M)$

heavy charged lepton

$$\mathcal{L}_{eff} = \sum_i C_i(M)\, O_i$$

تابعی از M و α

$d_i > n_i$ $\sim$ $F_{\mu\nu}$

$$O_i \sim \frac{1}{M^{d_i - 4}} \qquad d_i > n_i > 4$$

$d_i = 4$ به ازای

$F^{\mu\nu} F_{\mu\nu} \leftarrow$ marginal operator

$$\int_0^1 dt \ln \frac{\Lambda^2}{M^2 - t(1-t)q^2} - (-q^2 \to \mu^2)$$

$$\underline{\underline{\mu^2, |q^2| \ll M^2}} \qquad -\int_0^1 dt\; t(1-t)\,\frac{q^2+\mu^2}{M^2} = -\frac{1}{6}\,\frac{q^2+\mu^2}{M^2} \ll 1$$

خوبه یا بده؟

Chiral theories with SSB

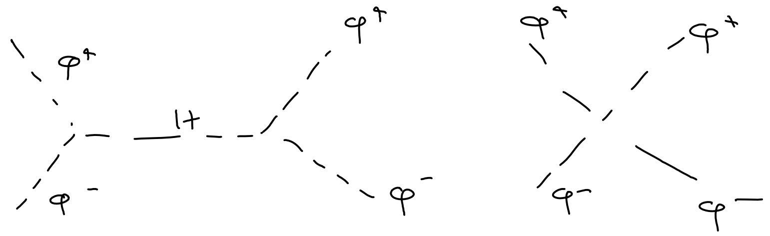
$\downarrow$

non-decoupling

coupling $\propto$ M $\longrightarrow$ اون وقت چی؟

$$f_t = \frac{m_t}{v/\sqrt{2}} = \frac{g}{\sqrt{2}}\,\frac{m_t}{m_W}$$

Non-linear sigma model



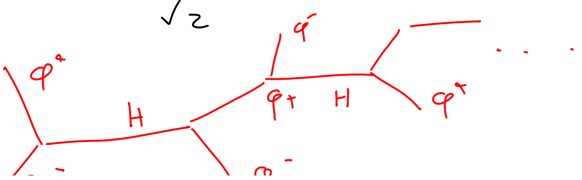
$$-i\,\frac{1}{2}\,\frac{i}{q^2-M_H^2}\left(-ig\,\frac{M_H^2}{2m_W}\right)^2(\varphi^+\varphi^-)^2 \simeq$$

$$\frac{g^2}{8}\left(\frac{1}{M_H^2}+\frac{q^2}{M_H^4}\right)\frac{M_H^4}{m_W^2}\,(\varphi^+\varphi^-)^2$$

$$-\frac{g^2}{8M_W^2}\,\varphi^+\varphi^-\,\Box(\varphi^+\varphi^-)$$ no m_H^2 dependence

$$\frac{v^2}{4}\,\mathrm{Tr}\left[\partial_\mu U\,\partial^\mu U\right] \qquad U \equiv e^{\frac{iG^i\sigma^i}{v}}$$

$$G^+ = -\frac{G^1+iG^2}{\sqrt{2}} = -i\varphi^+ \qquad G^3 = \sqrt{2}\,\mathrm{Im}\,\varphi^0$$



φ^- $\quad$ φ

$$\Phi \equiv \tilde{\varphi}\varphi = \frac{v_{qH}}{\sqrt{2}} U$$

شیر $\quad \pi^i \leftrightarrow \varphi^i$

$U^\dagger U = 1$

↳ no contact term $\times$

$\Delta\rho$

(t, b)

(t', b') $\quad W_3^\mu = \cos\theta_w Z^\mu + \sin\theta_w \gamma^\mu$

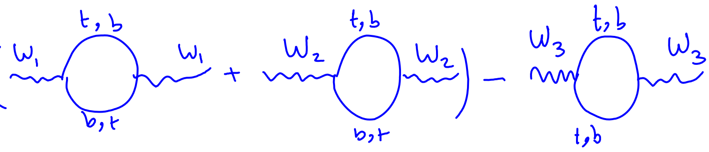
Correcton to $\cos^2\theta_w M_Z^2 \equiv$ Correction to $W_\mu^3 W^{3\mu}$

$$\Delta\rho = \delta\left(\frac{M_{W^\pm}^2}{M_{W_3}^2}\right) - 1 = \frac{M_{W^\pm}^2 + \delta M_{W^\pm}^2}{M_{W_3}^2 + \delta m_{W_3}^2} - 1 \simeq$$

$$\frac{1}{m_W^2}\left(\frac{\delta m_{W_1}^2 + \delta m_{W_2}^2}{2} - \delta m_{W_3}^2\right)$$

$$m_{W^\pm}^2 W_\mu^\pm W^{-\mu} = m_{W^\pm}^2 \frac{W_{1\mu}W^{1\mu} + W_{2\mu}W^{2\mu}}{2}$$

$\Pi_{ab}(0) \leftarrow$ Vacuum polarization

$\Delta\rho \cdot m_W^2 \sim \frac{1}{2}($ 

$$\sim \frac{1}{2}\left(\Pi_{11}(0) + \Pi_{22}(0)\right) - \Pi_{33}(0)$$

Veltman, 1977 برای لپتون‌ها حساب کرده بود

$$\Delta\rho = \frac{3\alpha}{16\pi \sin^2\theta_W} \frac{1}{m_W^2}\left(m_t^2 + m_b^2 - \frac{2m_t^2 m_b^2}{m_t^2 - m_b^2} \ln\frac{m_t^2}{m_b^2}\right)$$

اگر $m_t = m_b$ $\quad \Delta\rho = 0$

حد $m_t \gg m_b$

$$\Delta\rho \simeq \frac{3\alpha}{16\pi \sin^2\theta_W} \frac{m_t^2}{m_W^2}$$

non-decoupling

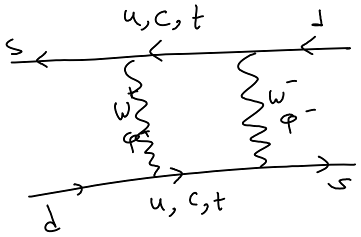
دقت کنید که از جفت‌شدگی Yukawa استفاده نکردیم.

FCNC

$K^0 \longleftrightarrow \bar{K}^0$

$\bar{s}\gamma_5 d \qquad \bar{d}\gamma_5 s$

$\bar{s}d \longleftrightarrow s\bar{d}$



Lee Gaillard فرض: $m_c \ll m_W \rightarrow$

$m_t \longleftrightarrow$ decoupling?

$$\mathcal{L}_{eff}^{|\Delta s|=2} = \frac{\alpha G_F}{4\sqrt{2}\pi \sin^2\theta_W} \sum_{i,j=c,t} (V_{is}^* V_{id})(V_{js}^* V_{jd})$$

$$E(x_i, x_j)\, \bar{s}\gamma_\mu L d \;\; \bar{s}\gamma^\mu L d$$

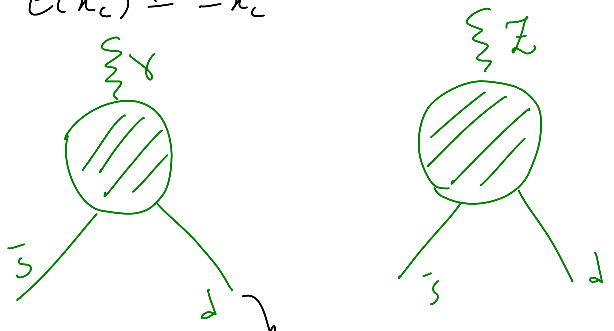
$$x_i \equiv \frac{m_i^2}{m_W^2}$$

$$E(x_t) \equiv E(x_t, x_t) = -\frac{3}{2}\left(\frac{x_t}{x_t-1}\right)^3 \ln x_t$$

$$-\left[\frac{1}{4} - \frac{9}{4}\frac{1}{x_t-1} - \frac{3}{2}\frac{1}{(1-x_t)^2}\right] x_t$$

$$E(x_t) \simeq -\frac{1}{4}\frac{m_t^2}{m_W^2}$$

$$E(x_c) \simeq -x_c$$



γ-penguin　　مراتب بالاتر $F^{\mu\nu}$　$\bar{s}\sigma^{\mu\nu}d$　　Z-penguin

$\propto \ln\frac{m_t}{m_c, m_u}$　　　　$\downarrow$ $\propto m_t^2$

$\Delta\rho$ FCNC $\propto m_t^2$

$\Delta\rho \leftarrow \cancel{\ln m_H}$

$\leftarrow \ln\frac{m_H}{m_W}$

$Zb\bar{b}$

Barbieri 4.10

کتاب نارنجی (باید کتاب نارنجی را ازش بگیرید.)

اگر تئوری ما کایرال باشد SSB هم داشته باشیم بازهم

می‌توانیم decoupling داشته باشیم. مثلاً اگر جرم ذرات جدید

با مکانیزمی غیر از هیگز داده شود که تحت الکتروضعیف ناوردا است.

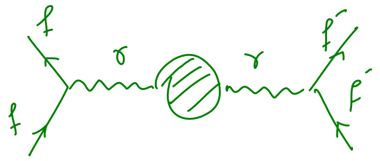
مکانیزم seesaw

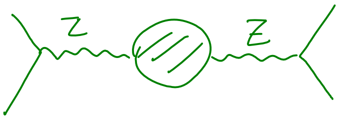
$\frac{1}{m}$

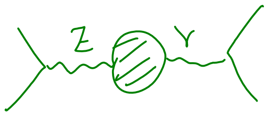
Oblique corrections

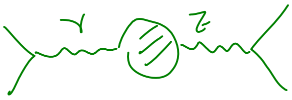
S, T & U parameters

تصحیحات به خاطر ذرات
سنگینی که مستقیم به ذرات
نهایی جفت نمی‌شوند









Star prescription   Kennedy Lynn 1989

$$\begin{matrix} e \\ s^2 \; (\equiv \sin^2\theta_W) \end{matrix} \longrightarrow \begin{matrix} e_*(q^2) \\ s_*^2 \; (q^2) \end{matrix}$$

$$\mathcal{L}_{eff} = e_*^2 Q Q' \bar{f}\gamma_\mu f \frac{1}{q^2} \bar{f}'\gamma^\mu f'$$

$$+ \frac{e_*^2}{c_*^2 s_*^2} \left(\bar{f}\gamma_\mu [I_3 L - s_*^2 Q] f\right] \frac{Z_*}{q^2 - M_*^2} \left(\bar{f}'\gamma_\mu [I_3' L - s_*^2 Q'] f'\right)$$

$$\frac{1}{2} \Pi_{\gamma\gamma} \, g_{\mu\nu} A^\mu A^\nu + \frac{1}{2} \Pi_{ZZ} \, g_{\mu\nu} Z^\mu Z^\nu +$$

$$\Pi_{Z\gamma} \, g_{\mu\nu} Z^\mu A^\nu + \Pi_{WW} \, g_{\mu\nu} W^{+\mu} W^{-\nu}$$

$q_\mu q_\nu \leftarrow$ ignored $\leftarrow$ $q_\mu \; \bar{f}\gamma^\mu \gamma_5 f = 2m_f \bar{f}\gamma_5 f$

$$\mathcal{L}_{eff} = \left(e Q \bar{f}\gamma_\mu f \quad \frac{e}{cs} \bar{f}\gamma_\mu (I_3 L - s^2 Q) f\right)$$

$$\begin{pmatrix} q^2 - \Pi_{\gamma\gamma} & -\Pi_{Z\gamma} \\ -\Pi_{Z\gamma} & q^2 - M_0^2 - \Pi_{ZZ} \end{pmatrix}^{-1} \begin{pmatrix} eQ' \bar{f}'\gamma^\mu f' \\ \frac{e}{cs} \bar{f}'\gamma^\mu (I_3' L - s^2 Q') f' \end{pmatrix}$$

$$\Pi_{\gamma\gamma} = q^2 \Pi'_{\gamma\gamma} \qquad \Pi_{ZZ} = q^2 \Pi'_{ZZ}$$

کتاب این را نوشته ما استفاده نکرده

$$\Pi_{\gamma Z} = q^2 \Pi'_{\gamma Z}$$

فوتون بی جرم است .

$$M_0^2 = \frac{e^2 v^2}{4 c^2 s^2} \leftarrow \text{bare mass}$$

$$\left(\left(e Q \bar{f} \gamma_\mu f \quad \frac{e}{cs} \bar{f} \gamma_\mu (I_3 L - s^2 Q) f \right)\right.$$

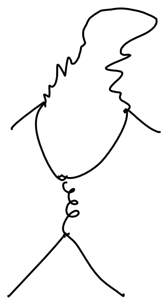
$$\begin{pmatrix} \frac{1}{q^2(1-\Pi'_{\gamma\gamma})} & \frac{\Pi'_{Z\gamma}}{q^2 - M_0^2} \\ \frac{\Pi'_{Z\gamma}}{q^2 - M_0^2} & \frac{1}{q^2 - M_0^2 - \Pi_{ZZ}} \end{pmatrix} \begin{pmatrix} e Q' \bar{f}' \gamma^\mu f' \\ \frac{e}{cs} \bar{f}' \gamma^\mu (I_3' L - s^2 Q') f' \end{pmatrix}$$

تقریب اول $\Downarrow$

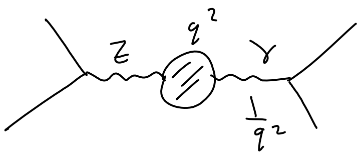
$$\simeq \frac{e^2}{1 - \Pi'_{\gamma\gamma}} Q \bar{f} \gamma_\mu f \frac{1}{q^2} Q' \bar{f}' \gamma_\mu f'$$

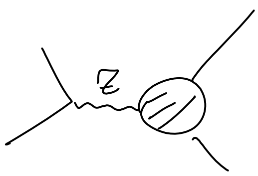
$$+ \frac{e^2}{c^2 s^2} \bar{f} \gamma_\mu \left[I_3 L - (s^2 - cs \Pi_{Z\gamma}) Q \right] f$$

$$\frac{1}{q^2 - M_0^2 - \Pi_{ZZ}} \left(\bar{f}' \gamma_\mu \left[I_3' L - (s^2 - cs \Pi_{Z\gamma}) Q' \right] f' \right.$$



دیاگرام پنگوئن





$$\frac{1}{q^2 - M_0^2 - \Pi_{ZZ}} \qquad \overset{\text{pole}}{\searrow} \quad m_Z^2 - M_0^2 - \Pi_{ZZ}(M_Z^2) = 0$$

جرم فیزیکی که خیلی خوب اندازه گیری شده .

$$q^2 - M_0^2 - \Pi_{ZZ}(q^2) = q^2 - M_Z^2 - (q^2 - M_Z^2) \left. \frac{d\Pi_{ZZ}}{dq^2} \right|_{q^2 = M_Z^2}$$

$$-\Pi_{res} \simeq \left(1 - \frac{d\Pi_{ZZ}}{dq^2}\bigg|_{q^2=M_Z^2}\right)\left(q^2 - M_Z^2 - \Pi_{res}\right)$$

$$\Pi_{res} = \Pi_{ZZ}(q^2) - \Pi_{ZZ}(M_Z^2) - (q^2 - M_Z^2)\frac{d\Pi_{ZZ}}{dq^2}\bigg|_{q^2=M_Z^2}$$

$$\frac{1}{e_*^2} = \frac{1}{e^2}\left(1 - \Pi'_{\gamma\gamma}\right) \simeq \frac{1}{4\pi\alpha}\left\{1 - \left[\Pi'_{\gamma\gamma}(q^2) - \Pi'_{\gamma\gamma}(0)\right]\right\}$$

$$\frac{1}{4\pi\alpha} = \frac{1}{e^2}\left[1 - \Pi'_{\gamma\gamma}(0)\right]$$

$$s_*^2 = s^2 - cs\,\Pi'_{Z\gamma}$$

$$Z_* = \frac{\left(\frac{e^2}{c^2 s^2}\right)}{\left(\frac{e_*^2}{c_* s_*}\right)}\left(1 + \frac{d\Pi_{ZZ}}{dq^2}\bigg|_{q^2=M_Z^2}\right) \simeq$$

$$1 + \frac{d\Pi_{ZZ}}{dq^2}\bigg|_{q^2=M_Z^2} - \Pi'_{\gamma\gamma} - \frac{c^2 - s^2}{cs}\Pi'_{Z\gamma}$$

$$M_*^2 = M_Z^2 + \Pi_{res} =$$

$$M_Z^2 + \Pi_{ZZ}(q^2) - \Pi_{ZZ}(M_Z^2) - (q^2 - M_Z^2)\frac{d\Pi_{ZZ}}{dq^2}\bigg|_{q^2=M_Z^2}$$

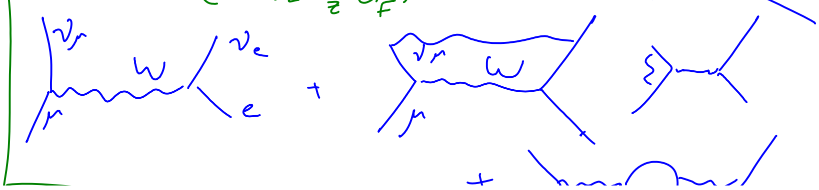
$$\Pi(q^2) = \underbrace{\Pi(q_0^2) + (q^2 - q_0^2)\Pi'}_{\text{UV divergent}} + \underbrace{\cdots}_{\text{UV finite}}$$

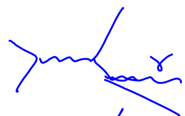
محدود بودن e_* و M_* محرز است.

$Z^* \to$ finite! $\to$ ۸.۴ تمرین

$S_* \to ?$ $\nearrow$ نامحدود s

$$\sin 2\theta_W = \left(\frac{e_*^2(M_Z^2)}{\sqrt{2}\, m_Z^2 G_F}\right)^{1/2}$$





$$s_*^2 = \sin^2\theta_w\Big|_Z - \frac{c^2 s^2}{c^2 - s^2}\left(\Pi'_{\gamma\gamma} + \frac{\Pi_{WW}(0)}{c^2 M_Z^2} - \frac{\Pi_{ZZ}}{M_Z^2}\right) - cs\,\Pi'_{Z\gamma}(q^2)$$

$$\Pi_{WW}(0) - c^2\,\Pi_{ZZ}(0) \rightarrow$$ finite?

Left right asymmetry

$$A_{LR} \equiv \frac{\sigma(e_L^- e^+ \to Z) - \sigma(e_R^- e^+ \to Z)}{\sigma(e_L^- e^+ \to Z) + \sigma(e_R^- e^+ \to Z)}$$

polarized e

$$= \frac{8\left(\frac{1}{4} - \sin^2\theta_w\right)}{1 + (1 - 4\sin^2\theta_w)^2} \simeq 8\left(\frac{1}{4} - \sin^2\theta_w\right)$$

$$\mathcal{L} \propto Z_\mu \left[\bar{e}\, a_L \gamma^\mu \underset{\frac{1-\gamma_5}{2}}{P_L}\, e + \bar{e}\, a_R \gamma^\mu \underset{\frac{1+\gamma_5}{2}}{P_R}\, e\right]$$

$$= Z_\mu\left[\bar{e}\,\frac{a_L + a_R}{2}\gamma^\mu e + \frac{a_R - a_L}{2}\,\bar{e}\,\gamma^\mu\gamma_5 e\right]$$

$$e_L^- = \frac{1-\gamma_5}{2}\, e$$

$$a_L = -\frac{1}{2} + \sin^2\theta_w$$

$$a_R = \sin^2\theta_w$$

از [illegible]

$$\sigma(e_L e^+ \to Z) \propto |a_L|^2 = \left(-\frac{1}{2} + \sin^2\theta_w\right)^2$$

$$\sigma(e_R e^+ \to Z) \propto |a_R|^2 = \sin^4\theta_w$$

$$A_{LR} = \frac{\left(-\frac{1}{2} + \sin^2\theta_w\right)^2 - \sin^4\theta_w}{\sim \quad + \sim} =$$

$$\frac{-\frac{1}{2}\left(-\frac{1}{2} + 2\sin^2\theta_w\right)}{\frac{(1 - 4\sin^2\theta_w)^2 + 1}{8}} = \frac{8\left(\frac{1}{4} - \sin^2\theta_w\right)}{1 + (1 - 4\sin^2\theta_w)^2}$$

درجه دقتی

$$\simeq 8\left(\frac{1}{4} - \sin^2\theta_w\right)$$

$$\frac{1}{4} - \sin^2\theta_w \simeq$$

خیلی حساس به $\sin^2\theta_w \big|_Z$

سه جور تعریف

$$\begin{cases} \sin^2\theta_w \big|_Z \leftarrow A_{LR} \\ \sin\theta^* \\ \sin\theta = 1 - M_W^2/M_Z^2 \end{cases}$$

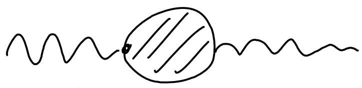
$$\Pi_{\gamma\gamma} = e^2\, \Pi_{QQ}$$

$$\Pi_{Z\gamma} = \frac{e^2}{cs}\left(\Pi_{3Q} - s^2\,\Pi_{QQ}\right)$$

$$\Pi_{ZZ} = \frac{e^2}{c^2 s^2}\left(\Pi_{33} - 2s^2\Pi_{3Q} + s^4\Pi_{QQ}\right)$$

$$\Pi_{WW} = \frac{e^2}{s^2}\,\Pi_{11}$$

$\Pi_{22} = \Pi_{11} \quad \leftarrow \quad$ Unbroken $U(1)_{em}$



$$\Pi_{ij} = \langle J_i \; J_j \rangle$$

$\Pi_{22} = \Pi_{11}$ اثبات کنید که *

$$\Rightarrow \quad \Pi_{11} = \Pi_{22}$$

$$\begin{pmatrix} t \\ b \end{pmatrix}$$

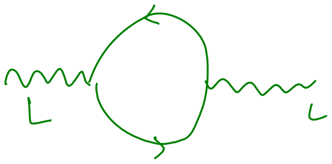
$$\Pi_{LL}(m_1^2, m_2^2; q^2) = \Pi_{RR}(m_1^2, m_2^2; q^2)$$

$$= -\frac{12}{(4\pi)^2}\int_0^1 dt\, \ln\frac{\Lambda^2}{M^2 - t(1-t)q^2}\left[t(1-t)q^2 - \frac{M^2}{2}\right]$$

$$\Pi_{LR}(m_1^2, m_2^2; q^2) = \Pi_{RL}(m_1^2, m_2^2; q^2) =$$

$$-\frac{12}{(4\pi)^2}\int_0^1 dt\, \ln\frac{\Lambda^2}{M^2 - t(1-t)q^2}\,\frac{1}{2}m_1 m_2$$

$$-\frac{12}{(4\pi)^2}\int_0^1 dt \; \mathrm{Ln}\frac{\Lambda^2}{M^2-t(1-t)q^2}\;\frac{1}{2}m_1 m_2$$



$=$

$$(-1)\int\frac{d^4k}{(2\pi)^4}\mathrm{Tr}\left\{(i\gamma^\mu)\frac{1-\gamma^5}{2}\frac{i(\cancel{k}+m_1)}{k^2-m_1^2}\right.$$

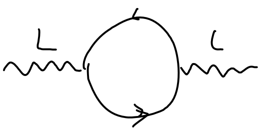
$$\left. i\gamma^\nu\frac{1-\gamma^5}{2}\frac{i(\cancel{k}+\cancel{q}+m_2)}{(k+q)^2-m_2^2}\right\} =$$

$$-\int\frac{d^4k}{(2\pi)^4}\mathrm{Tr}\left[\gamma^\mu\cancel{k}\gamma^\nu(\cancel{k}+\cancel{q})\frac{1+\gamma^5}{2}\right]\times$$

$$\frac{1}{(k^2-m_1^2)\left[(k+q)^2-m_2^2\right]}$$

$$\frac{1}{(k^2-m_1^2)((k+q)^2-m_2^2)}=\int_0^1 dx\frac{1}{(l^2-\Delta)^2}$$

$$l=k+xq \qquad \Delta=xm_2^2+(1-x)m_1^2-x(1-x)q^2$$



$$=-\frac{4i}{(4\pi)^{d/2}}\int_0^1 dx\frac{\Gamma(2-\frac{d}{2})}{\Delta^{2-d/2}}$$

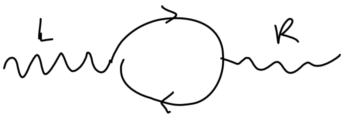
$$\left[g^{\mu\nu}\left(x(1-x)q^2-\frac{1}{2}(xm_2^2+(1-x)m_1^2)\right)\right.$$

$$-x(1-x)q^\mu q^\nu$$

$$\mathrm{Tr}\left\{\gamma^\mu\gamma^\nu\gamma^\alpha\gamma^\beta\gamma^5\right\}\propto\varepsilon^{\mu\nu\alpha\beta} \qquad \gamma^5$$ جای

$$A_\mu A_\nu q_\alpha X_\beta\,\varepsilon^{\mu\nu\alpha\beta}$$

x_ρ ? $\longrightarrow$ $\Pi_{LL} = \Pi_{RR}$



$$= -\frac{2i}{(4\pi)^{d/2}} \int_0^1 dx \, \frac{\Gamma(2-\frac{d}{2})}{\Delta^{2-d/2}} \, g^{\mu\nu} m_1 m_2$$

$$=(-1)\int \frac{d^4k}{(2\pi)^4} \, \mathrm{Tr}\Big[(i\gamma^\mu)\frac{1-\gamma_5}{2}\frac{i(\not k+m_1)}{k^2-m_1^2}(i\gamma^\nu)$$

$$\frac{1+\gamma^5}{2}\frac{i(\not k+\not q+m_2)}{(k+q)^2-m_2^2}$$

$$\Pi_{LR} = \Pi_{RL}$$

$$\Pi_{VV} = \Pi_{L+R,\,L+R} = 2(\Pi_{LL}+\Pi_{LR})$$

$$\Pi_{QQ} = Q_t^2\,\Pi_{VV}(m_t^2, m_t^2, q^2) + Q_b^2\,\Pi_{VV}(m_b^2, m_b^2, q^2)$$

$$\Pi_{3Q} = \frac{Q_t}{2}\Pi_{LV}(m_t^2, m_t^2, q^2) - \frac{Q_b}{2}\Pi_{LV}(m_b^2, m_b^2, q^2)$$

$$= \frac{1}{4}\Big[Q_t\,\Pi_{VV}(m_t^2, m_t^2, q^2) - Q_b\,\Pi_{VV}(m_b^2, m_b^2, q^2)$$

$$\Pi_{33}(q^2) = \frac{1}{4}\Big[\Pi_{LL}(m_t^2, m_t^2, q^2) + \Pi_{LL}(m_b^2, m_b^2, q^2)\Big]$$

$$\Pi_{11}(q^2) = \frac{1}{2}\Pi_{LL}(m_t^2, m_b^2, q^2)$$

$$\Pi_{LL}(m_t^2, m_t^2, q^2) \simeq \frac{6}{(4\pi)^2}\, m_t^2 \,\ln\frac{\Lambda^2}{m_t^2}$$

$$\Pi_{LL}(m_t^2, m_b^2, q^2) \simeq \frac{3}{(4\pi)^2}\, m_t^2 \left(\ln\frac{\Lambda^2}{m_t^2} + \frac{1}{2}\right)$$

$$\Pi_{11}(0) - \Pi_{33}(0) \simeq \frac{1}{2}\Pi_{LL}(m_t^2, m_b^2, 0) -$$

$$\frac{1}{4}\Pi_{LL}(m_t^2, m_t^2, 0) \simeq \frac{3}{64\pi^2} m_t^2$$

vector like

$$\Pi_{VV}(m_t^2, m_t^2, q^2) =$$

$$\underbrace{q^2}_{\text{انتظار داشتیم}} \left\{ - \frac{24}{(4\pi)^2} \int_0^1 t(1-t) \log \frac{\Lambda^2}{m_t^2 - t(1-t)q^2} \, dt \right.$$

$m_t \to \infty \Rightarrow \Pi_{VV} \to 0$ decoupling

possible non-decoupling radiative corrections $\left\{ \begin{array}{l} S \\ T \\ U \end{array} \right.$ ← oblique parameter

Peskin Takeuchi, 1990

no coupling $\propto M$

$$\Pi_{ij}(q^2) = \underbrace{\Pi_{ij}(0)}_{O(M^2)} + \underbrace{\left.\frac{d\Pi_{ij}}{dq^2}\right|_{q^2=0} q^2}_{O(q^2)} + \cdots$$

مرتبه بالاتر $\rightarrow \left(\frac{q^2}{M^2}\right)^n$

$$\underset{\Pi}{8} = 2 \times \underset{\Pi'}{4}$$

مورد

نظر اول

$4 \searrow (i,j) \begin{cases} (1,1) = (2,2), (3,3), (3,Q), (Q,Q) \\ (W^+, W^-), (Z,Z), (\gamma,\gamma), (Z,\gamma) \end{cases}$

$\Pi_{QQ} = 0 \qquad \Pi_{3Q} = 0 \qquad 8 - 2 = 6$

$\longrightarrow$ normalization of $g \; g' \; v$

$$\left.\begin{array}{l} \Pi(0) \\ \frac{d\Pi}{dq^2} \end{array}\right\} \longrightarrow \text{correction to operators } \begin{array}{l} d=2 \\ d=4 \end{array}$$

$M_Z \quad G_F \quad \alpha$ به عبارت دیگر نیست

پس ۳ تا از ۶ تا input هستند نه پیش بینی.

Outputs (prediction) $= \underbrace{3}_{S \;\; U \;\; T}$

$$\alpha S \equiv 4e^2 \left[\Pi'_{33}(0) - \Pi'_{3Q}(0) \right]$$

$$\alpha T \equiv \frac{e^2}{c^2 s^2 M_Z^2} \left[\Pi_{11}(0) - \Pi_{33}(0) \right]$$

$$\alpha U \equiv 4e^2 \left[\Pi'_{11}(0) - \Pi'_{33}(0) \right]$$

renormalizability $\rightarrow$ No UV divergence $\rightarrow$ U, T, S

$\cancel{F^i_{\mu\nu} B^{\mu\nu}} \longrightarrow S \not\to \infty$

Original Lagrangian

Symmetry $(i \longleftrightarrow j)$

$$\sum_{i=1}^{3} F^i_{\mu\nu} F^{i\mu\nu} \qquad\qquad \frac{g v^2}{4} \sum_{i=1}^{3} A^i_\mu A^{i\mu}$$

$$\Downarrow$$

No UV divergent correction to T and U

$U(p)$ to $O\left(\frac{q^4}{M^2}\right)$

یادآوری

$$\frac{1}{e_*^2} \simeq \frac{1}{4\pi\alpha} \left\{ \frac{1}{e_*^2} \simeq \frac{1}{4\pi\alpha} \left\{ 1 - \Pi'_{\gamma\gamma}(q^2) - \Pi'_{\gamma\gamma}(0) \right\} \right\}$$

$$s_*^2 - \sin^2\theta_w \Big|_Z \simeq \frac{\alpha}{c^2 - s^2}\left[\frac{S}{4} - c^2 s^2 T\right]$$

$$Z_* = 1 + \frac{\alpha}{4c^2s^2} S$$

$$M_*^2 \simeq M_Z^2$$ 4-fermi ضریب

$$\mathcal{L}_{eff}^{(NC)} = -\frac{8G_F}{\sqrt{2}} \rho_*(0) \left(\bar{f}\gamma_\mu [I_3 L - s_*^2 Q] f\right)\left(\bar{f}'\gamma^\mu (I_3' L - s_*^2 Q') f' \right)$$

$$\rho_*(0) = 1 + \alpha T$$

$$S = \frac{1}{2\pi}\left[1 - \frac{2}{3}\ln\frac{m_t}{m_b}\right]$$

$$T = \frac{3}{16\pi}\frac{1}{c^2s^2}\frac{1}{M_Z^2}\left[m_t^2 + m_b^2 - 2m_t^2 m_b^2\right.$$

اگر $m_t = m_b$ $\quad S = \frac{1}{2\pi} \quad T = 0$

← no decoupling!

S و T ، U اندازه‌گیری دقیق

m_t , m_H

T-parameter $\Delta\rho \rightarrow m_t = 175$ GeV

تقارن های سرتاسری

درکتاب فوسل (۸-۶۰) اشتباه است:

$$\mathcal{L}_{Yukawa} = f_u (\bar{u}_L \;\; \bar{d}_L) \begin{pmatrix} \varphi^{0*} \\ -\varphi^- \end{pmatrix} u_R + f_d (\bar{u}_L \;\; \bar{d}_L) \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_R$$

$$= (\bar{u}_L \;\; \bar{d}_L) \begin{pmatrix} \varphi^{0*} & \varphi^+ \\ -\varphi^- & \varphi^0 \end{pmatrix} \begin{pmatrix} f_u & 0 \\ 0 & f_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} + H.c.$$

دقت این سرتاسریه!

$$\Phi \equiv \begin{pmatrix} \varphi^{0*} & \varphi^+ \\ -\varphi^- & \varphi^0 \end{pmatrix}$$

$m_u = m_d$ در حد

$$\Phi \longrightarrow \Phi' = g_L \, \Phi \, g_R^*$$

g_L, g_R elements of $SU(2)_L$ and $SU(2)_R$

$$Tr(\Phi^\dagger \Phi) = H^2 + G^{i\,2}$$

$SO(4)$ $\equiv$ $SU(2)_L \times SU(2)_R$

$\Downarrow$

$SU(2)_V$

$$\Phi = \begin{pmatrix} \frac{v}{\sqrt{2}} & 0 \\ 0 & \frac{v}{\sqrt{2}} \end{pmatrix}$$

custodial symmetry

اسم یادتان باشه

به قیومیت

Sivikie, 1986

(global) weak isospin symmetry

$$g^\dagger \begin{pmatrix} \frac{v}{\sqrt{2}} & 0 \\ 0 & \frac{v}{\sqrt{2}} \end{pmatrix} g = \begin{pmatrix} \frac{v}{\sqrt{2}} & 0 \\ 0 & \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$g^\dagger \begin{pmatrix} f_u & \\ & f_d \end{pmatrix} g \neq \begin{pmatrix} f_u & \\ & f_d \end{pmatrix}$$

	$SU(2)_L \times SU(2)_R$	$SU(2)_V$
$A_\mu^i \quad (i=1,2,3)$	$(3,1)$	3

$A^i_\mu \quad (i=1,2,3) \qquad (3,1) \qquad 3$

$\bar{L}\gamma^\mu A^i_\mu \sigma^i L \qquad A^i_\mu \to R$ ندارد

$B^\mu \qquad (1,3)+(1,1) \qquad 3+1$

$B^\mu \bar{R}\begin{pmatrix} Y_u & \\ & Y_d \end{pmatrix} R \qquad \frac{Y}{2} = I_{3R} + \frac{B-L}{2}$

left-right symmetry

$$Q = I_{3L} + I_{3R} + \frac{(B-L)}{2}$$

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$S \sim \Pi'_{33} - \Pi'_{3Q} = \frac{1}{2}\Pi'_{3Y}$$

$$\begin{matrix} T \\ U \end{matrix} \sim \Pi_{11} - \Pi_{33} = \frac{1}{2}(\Pi_{11}+\Pi_{22}) - \Pi_{33}$$

mixing B_μ, A^3_μ

$S: \quad (3,3)+(3,1) \qquad 1+3+5$

$T,U: \quad (5,1) \qquad 5$

$$3\times 3 = \underbrace{1}_{\text{trace}} + \underbrace{3}_{\text{anti symmetric}} + 5 \longrightarrow \text{symmetric}$$

$$\frac{1}{2}(\Pi_{11}+\Pi_{22}) - \Pi_{33}$$

$$\Pi_{ij} = \begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \longleftarrow 3\times 3$$

custodial symmetry $\Rightarrow \frac{1}{2}(\Pi_{11} + \Pi_{22}) - \Pi_{33} = 0$

($m_t = m_b$ حد)

اما $S \neq 0$ حتی اگر ما تقارن custodial داشته باشیم.

کاری به technifermion نداریم.

Operator Formalism

$$O_T = (\varphi^\dagger D_\mu \varphi)(\varphi^\dagger D^\mu \varphi) - \frac{1}{3}\, \varphi^\dagger D_\mu D^\mu \varphi\, (\varphi^\dagger \varphi)$$

$$O_S = [\varphi^\dagger (F^i_{\mu\nu}\, \sigma^i)\varphi]\, B^{\mu\nu} \qquad \varphi \to (0, \frac{v}{\sqrt{2}})$$

که بنویسید چی می‌شه.

T, S ضریب O_T, O_S هستند.

به irrelevant

heavy particles responsible for S

new physics $\to M$ جرم

electroweak invariant

$$\sim \frac{1}{M^2}\, [\varphi^\dagger\, W^i_{\mu\nu}\, \sigma^i \varphi]\, B^{\mu\nu}$$

decoupling

Operator

اپراتورهای مرتبه‌ی بالاتر؟ ؟

Riccardo Barbieri

منبع

Lectures on the electroweak interactions

Scuola Normale Supriore, Pisa, Italy

فصل ۴

رقت
ρ بهتر 1 ppm

اوایل دهه ۹۰ قبل از کشف مستقیم t

$\rho \rightarrow m_t \rightarrow$ با دقت 30%

با داده‌ی فعلی دقت m_t از طریق غیرمستقیم → چند درصد

$m_t = 171.4 \pm 2.1$ GeV

custodial symmetry

Y_t ← $\overbrace{SU(2)_L \times SU(2)_R}$ را می‌شکند

g' نیز $SU(2)_L \times SU(2)_R$ را می‌شکند

اثر Higgs

$$\hat{S} = \frac{G_F m_W^2}{12\sqrt{2}\pi^2} \log m_W \qquad \hat{T} = -\frac{3G_F}{4\sqrt{2}\pi^2} tg^2\theta \log m_h$$

شکست custodial

یادآوری

$$tg\theta = \frac{g'}{g}$$

وجه تسمیه‌ی custodial symmetry

ρ را برابر 1 نگاه می‌دارد.

$m_h = 85^{+39}_{-28}$ GeV $\qquad m_h < 165$ GeV at 95% C.L.

$$\Pi_V(q^2) \simeq \Pi_V(0) + q^2 \Pi_V'(0) + \frac{(q^2)^2}{2!}\Pi_V''(0) + \cdots$$

$W \propto \Pi''_{33}$

$X \propto \Pi''_{3Q}$

$Y \propto \Pi''_{QQ}$

$V \propto \Pi''_{33} - \Pi''_{11}$

با بررسی این پارامترها را form factor می‌خوانند

precision

Z-pole $\quad e^- e^+ \to Z \quad$ 1 ppm

W mass

LEP1 1989–1995

Z-pole

LEP2

LEP2 $\quad \underbrace{e^+ e^- \to f\bar{f}}_{\text{asymmetries}}$

1% → عرصش انرژی بالاتر

$$\frac{q^2}{M_{NP}^2}$$

$$\Downarrow$$

$\hat{S} \quad \hat{T} \quad Y \quad W$

The minimal Set of electroweak Precision Parameters

hep-ph/0604111

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Pisa