Electroweak precision data

۲۰۱۰/۱۱/۲۵
۱۱:۳۷ ق.ظ

SM $\leftarrow$ تئوری پیمانه‌ای بازبهنجارش پذیر

tree level $\begin{cases} \to \text{neutral current} \\ \to m_{Z^0},\ m_{W^\pm} \\ \to A_{FB} \quad e^+e^- \to f\bar{f} \end{cases}$

radiative correction

LEP CDF

Gauge Sector

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

$$\begin{cases} m_Z = 91.150(30) \ \text{GeV} \ (\text{from LEP, SLC}) \\ \quad 91.1876 \pm 0.0021 \ \text{GeV} \quad \text{pdg 2014} \\ G_F = 1.16637(2) \times 10^{-5} \ \text{GeV}^{-2} \ (\text{from } \mu \to e\, \nu_\mu \bar{\nu}_e) \\ \alpha = 137.0359895(61)^{-1} \ (\text{from } g\text{-}2 \text{ of } e) \end{cases}$$

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

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

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

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

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

درجه بعد تئوری بازبهنجارش پذیر

marginal بعد $=4$ $\qquad \lambda\varphi^4,\ \partial_\mu\varphi\partial^\mu\varphi$

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

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

t
H
unknown particles } 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

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

m_t , m_H , new heavy particles

Peskin & Takeuchi, 1990

~~Technicolor~~

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

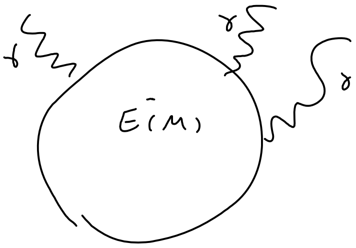
loop ??

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

$d_i > n_i$ که

$F_{\mu\nu}$

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

به ازای $d_i = 4$

$F^{\mu\nu} F_{\mu\nu} \leftarrow$ 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 بد؟

Chiral theories with SSB

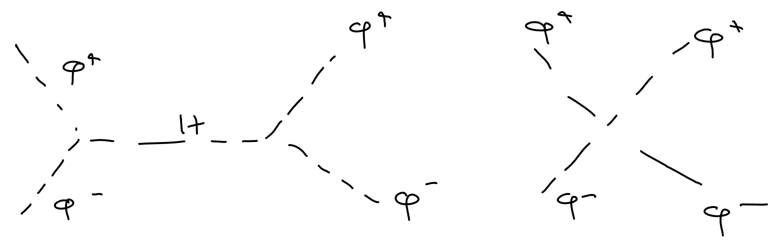
$\downarrow$

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



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

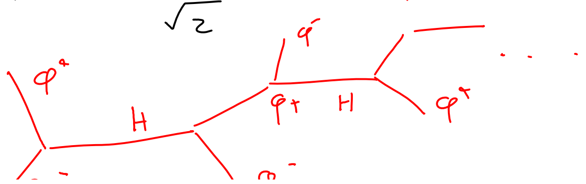
$$\frac{g^2}{8}\left(\frac{1}{M_H^2}+\frac{q^2}{M_H^4}\right)\frac{M_H^4}{m_W^2}\,(\varphi^+\varphi^-)^2$$

$$-\frac{g^2}{8M_W^2}\,\varphi^+\varphi^-\,\Box\,(\varphi^+\varphi^-)$$

no m_H^2 dependence

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

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



$/\varphi^-$ $\quad\quad$ $\backslash\varphi$

$$\Phi \equiv \tilde{\varphi}\varphi = \frac{v_{4H}}{\sqrt{2}}\, U$$

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

$U^\dagger U = 1$

↳ no contact term

sigma model

$$\Sigma = \sigma + i\tau\cdot\pi = (v_4 + s)\, U \qquad U = e^{i\frac{\tau\cdot\pi'}{v}}$$

$\pi' = \pi_4 \ldots$

$$\mathcal{L} = \frac{1}{4}\,Tr\left(\partial_\mu \Sigma\, \partial^\mu \Sigma^\dagger\right) + \frac{\mu^2}{4}\,Tr\left(\Sigma^\dagger\Sigma\right) - \frac{\lambda}{16}\left(Tr\,\Sigma^\dagger\Sigma\right)^2$$

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu s)^2 - 2\mu^2 s^2\right] + \frac{(v_4+s)^2}{4}\,Tr\left(\partial_\mu U\, \partial^\mu U^\dagger\right)$$

$\Delta\rho$

(t, b)

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

Correcton to $\cos^2\theta_W M_Z^2 \equiv$ Correction to $W^3_\mu W^{3\mu}$

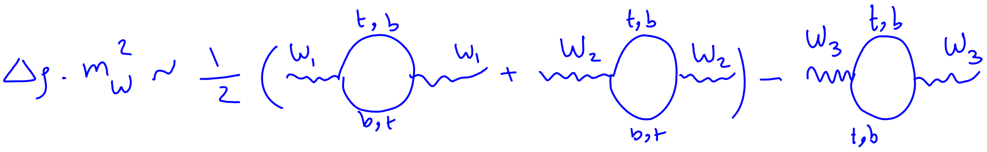
$$\Delta\rho = \delta\left(\frac{M_{W^4}^2}{M_{W_3}^2}\right) - 1 = \frac{M_{W^+}^2 + \delta M_{W^+}^2}{M_{W_3}^2 + \delta m_{W_3}^2} - 1 \simeq$$

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

w

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

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



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

Veltman, 1977 برای لپتون‌ها حساب کرده بود

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

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

جفت‌شدگی

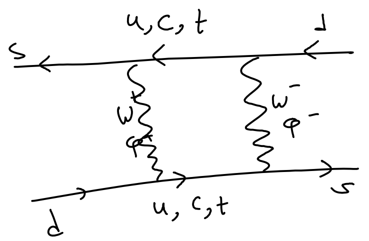
به دقت کنید که از Yukawa ها استفاده نکردیم.

FCNC

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

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

$\bar{s}d \leftrightarrow s\bar{d}$



وجود

Lee Gaillard فرض: $m_c \ll m_W \to$

$m_t \leftrightarrow$ decoupling?

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

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

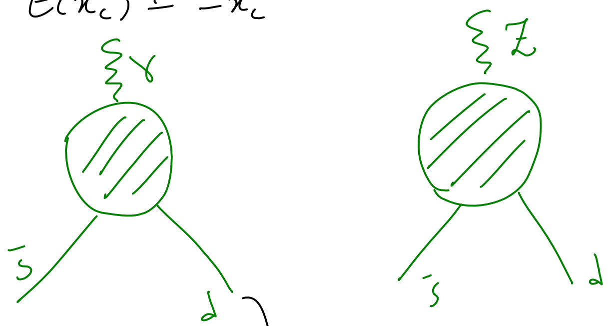
$$x_i \equiv \frac{m_i^2}{m_W^2}$$

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

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

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

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



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

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

$\Delta\rho$

FCNC $\propto m_t^2$

$\cancel{\propto m_H}$

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

$Zb\bar{b}$

Barbieri 4.10

کتاب نارنجی

اگر تئوری ما کایرال باشد SSB داشته باشیم باز هم

می توانیم decoupling داشته باشیم. مثلاً از جرم ذرات جدید

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

مکانیزم seesaw

$\frac{1}{m}$

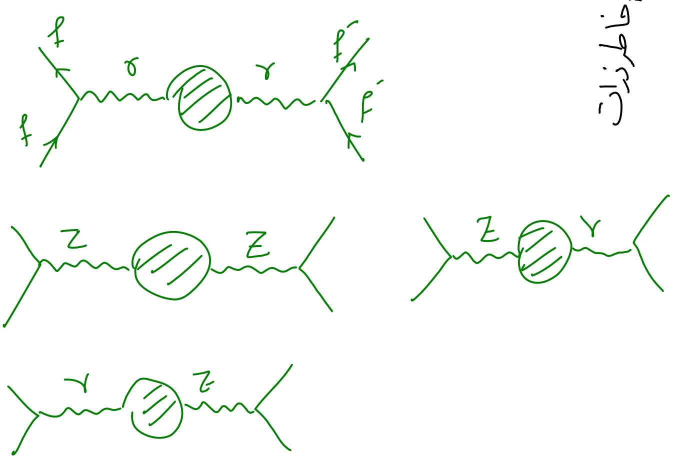
Oblique corrections

S, T & U parameters

تصحیحات به خاطر ذرات

سنگینی که مستقیم به ذرات

ناظر جفت نمی شوند



Star prescription   Kennedy Lynn 1989

$$e \qquad\qquad\qquad\qquad e_*(q^2)$$
$$s^2 \ (\equiv \sin^2\theta_W) \longrightarrow S_*^2(q^2)$$

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

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

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

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

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

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

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

$$\mathcal{L}_{eff} = \Big(eQ\,\bar{f}\gamma_\mu f \qquad \frac{e}{cs}\bar{f}\gamma_\mu (I_3 L - s^2 Q) f \Big)$$

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

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

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

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

کتاب این را نوشته اما استفاده نکرده

$= \; \overset{\gamma}{\sim}\times\overset{Z}{\sim}\times\overset{\gamma}{\sim}$ فوتون بی جرم است.

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

$$\Big(eQ\,\bar{f}\gamma_\mu f \qquad \frac{e}{cs}\bar{f}\gamma_\mu (I_3 L - s^2 Q) f \Big)$$

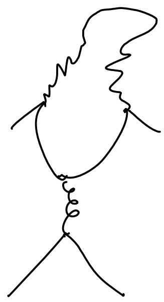
$$\begin{pmatrix} \frac{1}{q^2(1 - \Pi'_{\gamma\gamma})} & \frac{\Pi'_{Z\gamma}}{q^2 - M_0^2} \\ \frac{\Pi'_{Z\gamma}}{q^2 - M_0^2} & \frac{1}{q^2 - M_0^2 - \Pi_{ZZ}} \end{pmatrix} \begin{pmatrix} eQ'\,\bar{f}'\gamma^\mu f' \\ \frac{e}{cs}\,\bar{f}'\gamma^\mu (I_3' L - s^2 Q') f' \end{pmatrix}$$

$\Downarrow$ تقریب اول

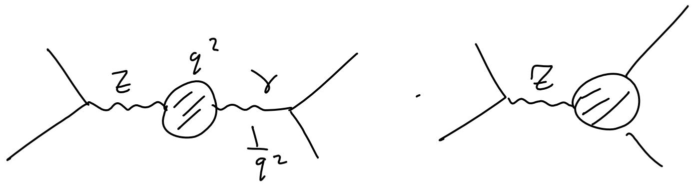
$$\simeq \frac{e^2}{1 - \Pi'_{\gamma\gamma}}\; Q\,\bar{f}\gamma_\mu f \;\frac{1}{q^2}\; Q'\,\bar{f}'\gamma_\mu f'$$

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

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



دیاگرام پنگوئن



pole

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

جرم فیزیکی که خیلی خوب اندازه‌گیری شده.

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

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

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

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

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

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

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

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

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

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

$$\Pi(q^2) = \Pi(q_0^2) + (q^2 - q_0^2)\Pi' + \cdots$$

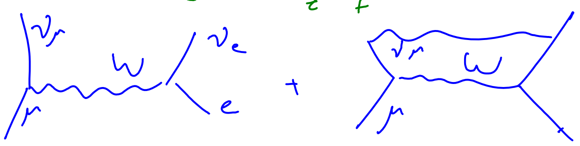
$$\underbrace{\qquad\qquad}_{\text{UV divergent}} \quad \underbrace{\qquad}_{\text{UV finite}}$$

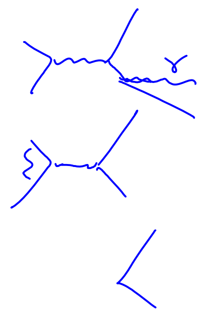
محدود بودن e_* و M_* محرز هست.

Z_* → finite? → تمرین ۸.۴

S_* → ? ↗ s پرمحدود

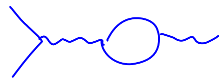
$$\boxed{\sin 2\theta_W = \left(\frac{e_*^2(M_Z^2)}{\sqrt{2}\, M_Z^2 G_F}\right)^{1/2}}$$





$$\sin^2\theta_W\big|_Z = s^2 + \delta s^2 = s^2 + 2sc\,\delta\theta_W = s^2 + \frac{2s^2c^2}{c^2 - s^2}\,\delta \ln(\sin 2\theta_W)$$

رابطه ۸-۲۹



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

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

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 و

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

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

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

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

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

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

از [illegible]

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

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

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

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

در حد دقت

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

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

خیلی حساس به A_{LR}

$$\sin^2\theta_w \big|_Z$$

سه جور تعریف

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

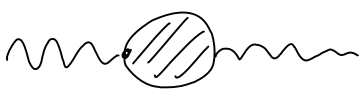
$$\Pi_{\gamma\gamma} = e^2\,\Pi_{QQ}$$

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

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

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

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



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

$\boxed{\Pi_{22} = \Pi_{11} \quad \text{اثبات کنید که} \ *}$

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

* اثبات کنید که $\Pi_{22} = \Pi_{11}$

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

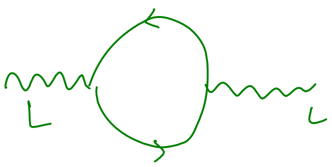
$$\begin{pmatrix} t \\ b \end{pmatrix}$$

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

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

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

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



$$=$$

$$(-1) \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr} \Big\{ (i\gamma^\mu) \frac{1-\gamma^5}{2} \frac{i(\not{k} + m_1)}{k^2 - m_1^2}$$

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

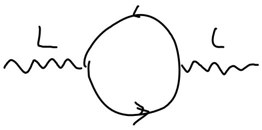
$$-\int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}\left[\gamma^\mu \not{k} \gamma^\nu (\not{k} + \not{q}) \frac{1+\gamma^5}{2} \right] \times$$

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

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

$$l = k + xq \qquad \Delta = x m_2^2 + (1-x) m_1^2 - x(1-x) q^2$$

$l = k + xq \qquad \Delta = x m_2^2 + (1-x) m_1^2 - x(1-x) q^2$



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

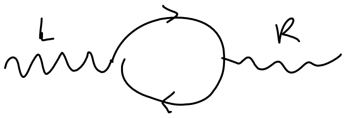
$$\Big[g^{\mu\nu} \Big(x(1-x) q^2 - \frac{1}{2} (x m_2^2 + (1-x) m_1^2) \Big)$$

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

$\mathrm{Tr}\{\gamma^\mu \gamma^\nu \gamma^\alpha \gamma^\beta \gamma^5\} \propto \varepsilon^{\mu\nu\alpha\beta} \qquad \gamma^5$ [illegible]

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

$X_\beta \;?\; \longrightarrow \qquad \Pi_{LL} = \Pi_{RR}$



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

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

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

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

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

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

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

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

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

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

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

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

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

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

vector like

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

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

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

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

Peskin Takeuchi, 1990

no coupling αM

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

$$\Pi_{ij}(q^2) = \underbrace{\Pi_{ij}(0)}_{O(M^2)} + \underbrace{\frac{d\,\Pi_{ij}}{dq^2}\Big|_{q^2=0} q^2}_{O(q^2)} + \cdots \quad \xrightarrow{\text{مرتبه بالاتر}} \left(\frac{q^2}{M^2}\right)^n$$

$\Pi \quad \Pi'$

$8 = 2 \times 4$ مورد

نظر اول

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

تا

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

$\longrightarrow$ normalization of g g' v

$\left.\begin{matrix} \Pi(0) \\ \frac{d\Pi}{dq^2} \end{matrix}\right\} \longrightarrow$ Correction to operators $d=2$, $d=4$

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

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 $\nearrow$ No UV $\xrightarrow{\text{divergence}}$ U, T, S

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

Original Lagrangian

Symmetry $(i \longleftrightarrow j)$

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

$$\Downarrow$$

No UV divergent correction to

T and U

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

یادآوری

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

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

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

$M_*^2 \simeq M_Z^2$ 4-fermi ضریب

$$\mathcal{L}^{(NC)}_{eff} = -\frac{8G_F}{\sqrt{2}} \rho_*(0) \left(\bar{f}\gamma_\mu \left[I_3 L - s_*^2 Q\right] f\right)\left(\bar{f}' \gamma^\mu \left(I'_3 L - s_*^2 Q'\right) f'\right)$$

$$f_A(0) = 1 + \alpha T$$

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

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

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

no decoupling!

اندازه‌گیری دقیق S و T و U

$$\swarrow$$

$m_t \,,\, m_H$

T- parameter $\quad \Delta\rho \longrightarrow m_t = 175\ \text{GeV}$

تقارن های سرتاسری

امتحان کنید

در کتاب فوسل (۹۰-۸) اشتباه است:

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

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

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

دقت! این سرتاسریه!

$m_u = m_d$ در حد

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

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

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

$$\uparrow$$

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

$$\Downarrow$$

$$SU(2)_V$$

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

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

اسم یادتان باشد
قیمومیتی

custodial symmetry

Sikivie, 1980

(global) weak isospin symmetry

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

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

$\bar{L} \gamma^\mu A_\mu^i \sigma^i L$ $\qquad A_\mu^i \to$ R به کاری
ندارد

B^μ		$(1,3) + (1,1)$	$3 + 1$

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

left-right symmetry

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

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

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

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

U

mixing B_μ, A_μ^3

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

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

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

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

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

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

($m_t = m_b$ حتی)

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.

که irrelevant

heavy particles responsible for S

new physics → M ↑ جرم

↓

electroweak invariant

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

decoupling

Operator

اپراتورهای مرتبه‌ی بالاتر؟ ؟

Riccardo Barbieri

منبع

Lectures on the electroweak interactions

Scuola Normale Supriore, Pisa, Italy

فصل ۴

ρ دقت بهتر 1 ppm

اوایل دهه ۹۰ قبل از کشف مستقیم t

$\rho \to m_t \to$ 30% با دقت

با داده‌ی فعلی دقت m_t از طریق غیرمستقیم → چند درصد

$m_t = 171.4 \pm 2.1$ GeV

custodial symmetry

Y_t — $SU(2)_L \times SU(2)_R$ را می‌شکند

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

اثر Higgs

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

شکست custodial

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

وجه تسمیه‌ی custodial symmetry

ρ را برابر 1 نگاه می‌دارد.

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

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

$$W \propto \Pi_{33}''$$

$$Y \propto \Pi_{QQ}'' \qquad X \propto \Pi_{3Q}''.$$

$$V \propto \Pi_{33}'' - \Pi_{11}''$$

بازبینی این پارامترها را form factor می‌خوانند

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

W mass

LEP1 1989–1995

Z-pole

LEP2

LEP2 $\quad \underbrace{e^+e^- \to f\bar{f}}_{\text{asymmetries}} \quad$ 1% $\to$ عیبش انرژی بالاتر q^2

$\Downarrow$ $\frac{v}{M^2_{NP}}$

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

The minimal Set of electroweak Precision Parameters

hep-ph/0604111

. . . . -- Strumia

$\downarrow$

Pisa