粒子物理标准模型拉氏量和费曼规则

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目　录

1 约定

本文采用自然单位制，各种约定主要遵从文献 [1]，推导和计算参考文献 [1, 2, 3, 4]。

Minkowski 度规张量

$$g_{\mu\nu} = g^{\mu\nu} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix}. \tag{1}$$

Pauli 矩阵

$$\sigma^1 = \begin{pmatrix} & 1 \\ 1 & \end{pmatrix}, \quad \sigma^2 = \begin{pmatrix} & -i \\ i & \end{pmatrix}, \quad \sigma^3 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}, \tag{2}$$

$$\sigma^\mu \equiv (1, \boldsymbol{\sigma}), \quad \bar{\sigma}^\mu \equiv (1, -\boldsymbol{\sigma}). \tag{3}$$

手征表示中的 Dirac 矩阵

$$\gamma^\mu = \begin{pmatrix} & \sigma^\mu \\ \bar{\sigma}^\mu & \end{pmatrix}, \quad \gamma_5 = \begin{pmatrix} -1 & \\ & 1 \end{pmatrix}. \tag{4}$$

左右手投影算符

$$P_{\mathrm{L}} \equiv \frac{1}{2}(1 - \gamma_5) = \begin{pmatrix} 1 & \\ & 0 \end{pmatrix}, \quad P_{\mathrm{R}} \equiv \frac{1}{2}(1 + \gamma_5) = \begin{pmatrix} 0 & \\ & 1 \end{pmatrix}. \tag{5}$$

Levi-Civita 张量约定取

$$\varepsilon^{0123} = \varepsilon^{123} = +1. \tag{6}$$

费曼规则约定：

- 对于指向相互作用顶点的动量 p，时空偏导数 ∂_μ 在动量空间费曼规则里贡献一个 $-ip_\mu$ 因子。

- 实线表示费米子，实线上的箭头表示费米子数流动的方向。

- 虚线表示标量玻色子，虚线上的箭头表示电荷数流动的方向。

- 螺旋线表示胶子；波浪线表示其它规范玻色子，波浪线上的箭头表示电荷数流动的方向。

- 点线表示鬼粒子，点线上的箭头表示鬼粒子数流动的方向。

- 如果没有额外箭头标记，动量方向与粒子线上的箭头方向一致；否则与额外箭头方向一致。

2 标准模型概述

粒子物理标准模型是一个 $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ 规范理论。模型中有三代费米子，包括三代中微子 $\nu_i = \nu_e, \nu_\mu, \nu_\tau$，三代带电轻子 $\ell_i = e, \mu, \tau$，三代上型夸克 $u_i = u, c, t$ 和三代下型夸克 $d_i = d, s, b$ ($i = 1, 2, 3$)。规范玻色子传递费米子间相互作用。

$\mathrm{SU(3)_C}$ 部分描述夸克的强相互作用，称为量子色动力学 (Quantum Chromodynamics, QCD)，相应的规范玻色子是胶子。$\mathrm{SU(2)_L \times U(1)_Y}$ 部分统一描述夸克和轻子的电磁和弱相互作用，称为电弱统一理论。理论中有一个 Higgs 二重态，通过 Brout–Englert–Higgs 机制引发规范群的自发对称性破缺，使 $\mathrm{SU(2)_L \times U(1)_Y}$ 群破缺为 $\mathrm{U(1)_{EM}}$ 群。$\mathrm{U(1)_{EM}}$ 规范理论称为量子电动力学 (Quantum Electrodynamics, QED)。

破缺前。理论中存在 4 个无质量的规范玻色子和 4 个 Higgs 自由度；左手费米子和右手费米子都没有质量。具有不同量子数。

破缺后，3 个规范玻色子与 3 个 Higgs 自由度结合，从而获得质量，成为 $W^\pm$ 和 Z^0 玻色子，传递弱相互作用；剩下的 1 个无质量规范玻色子是光子，即是 $U(1)_{\mathrm{EM}}$ 群的规范玻色子，传递电磁相互作用；剩下的 1 个中性 Higgs 自由度称为 Higgs 玻色子；与 Higgs 二重态的 Yukawa 耦合导致左手费米子和右手费米子获得质量，组合成 Dirac 费米子。

理论中的中微子没有右手分量，因而没有获得质量。1998 年实验发现中微子振荡，证明中微子具有质量，所以需要扩充标准模型才能正确描述中微子物理。

3 QCD 拉氏量和费曼规则

QCD 的拉氏量可表达成

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}(i\gamma^\mu D_\mu - m_q)q - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}, \quad q = u,d,s,c,b,t, \quad a = 1,\cdots,8, \tag{7}$$

其中

$$D_\mu = \partial_\mu - ig_{\mathrm{s}}G^a_\mu t^a, \quad G^{a\mu\nu} \equiv \partial^\mu G^{a\nu} - \partial^\nu G^{a\mu} + g_{\mathrm{s}}f^{abc}G^{b\mu}G^{c\nu}. \tag{8}$$

$SU(3)_{\mathrm{C}}$ 群基础表示生成元 $t^a = \lambda^a/2$，其中 λ^a 为 Gell-Mann 矩阵。生成元对易关系为 $[t^a,t^b] = if^{abc}t^c$。结构常数 f^{abc} 是全反对称的，其非零分量为

$$f_{123} = 1, \quad f_{147} = f_{246} = f_{257} = f_{345} = f_{516} = f_{637} = \frac{1}{2}, \quad f_{458} = f_{678} = \frac{\sqrt{3}}{2}. \tag{9}$$

由

$$\begin{aligned}
-\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} &= -\frac{1}{4}(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_{\mathrm{s}}f^{abc}G^b_\mu G^c_\nu)(\partial^\mu G^{a\nu} - \partial^\nu G^{a\mu} + g_{\mathrm{s}}f^{ade}G^{d\mu}G^{e\nu}) \\
&= -\frac{1}{2}[(\partial_\mu G^a_\nu)(\partial^\mu G^{a\nu}) - (\partial_\mu G^a_\nu)(\partial^\nu G^{a\mu})] - g_{\mathrm{s}}f^{abc}(\partial_\mu G^a_\nu)G^{b\mu}G^{c\nu} \\
&\quad - \frac{1}{4}g_{\mathrm{s}}^2 f^{abc}f^{ade}G^b_\mu G^c_\nu G^{d\mu}G^{e\nu},
\end{aligned} \tag{10}$$

可得

$$\begin{aligned}
\mathcal{L}_{\mathrm{QCD}} &= \sum_q [\bar{q}(i\gamma^\mu\partial_\mu - m_q)q + g_{\mathrm{s}}G^a_\mu\bar{q}\gamma^\mu t^a q] + \frac{1}{2}[(\partial_\mu G^a_\nu)(\partial^\nu G^{a\mu}) - (\partial_\mu G^a_\nu)(\partial^\mu G^{a\nu})] \\
&\quad - g_{\mathrm{s}}f^{abc}(\partial_\mu G^a_\nu)G^{b\mu}G^{c\nu} - \frac{1}{4}g_{\mathrm{s}}^2 f^{abc}f^{ade}G^b_\mu G^c_\nu G^{d\mu}G^{e\nu}.
\end{aligned} \tag{11}$$

设用于固定胶子场规范的函数 $G^a(x) = \partial^\mu G^a_\mu(x) - \omega^a(x)$，其中 $\omega^a(x)$ 是某个任意函数，规范固定条件是 $G^a(x) = 0$。这是 Lorenz 规范的推广，$\omega^a(x) = 0$ 对应于 Lorenz 规范。在路径积分量子化中，以中心为 $\omega^a(x) = 0$ 的 Gauss 权重对 $\omega^a(x)$ 作泛函积分，有

$$\int \mathcal{D}\omega^a \exp\left[-i\int d^4x \frac{1}{2\xi}(\omega^a)^2\right]\delta(G^a) = \exp\left[-i\int d^4x \frac{1}{2\xi}(\partial^\mu G^a_\mu)^2\right]. \tag{12}$$

可见，拉氏量中的规范固定项为

$$\mathcal{L}_{\text{QCD,GF}} = -\frac{1}{2\xi}(\partial^\mu G_\mu^a)^2. \tag{13}$$

ξ 的任何一个取值对应于一种规范。$\xi = 1$ 称为 Feynman-'t Hooft 规范，$\xi = 0$ 称为 Landau 规范。于是，胶子传播子相关拉氏量为

$$\begin{aligned}
\mathcal{L}_{\text{QCD,prop}} &= \frac{1}{2}\left[(\partial_\mu G_\nu^a)(\partial^\nu G^{a\mu}) - (\partial_\mu G_\nu^a)(\partial^\mu G^{a\nu}) - \frac{1}{\xi}(\partial^\mu G_\mu^a)^2\right] \\
&\to \frac{1}{2}G_\mu^a\left[g^{\mu\nu}\partial^2 - \left(1 - \frac{1}{\xi}\right)\partial^\mu\partial^\nu\right]G_\nu^a. \tag{14}
\end{aligned}$$

变换到动量空间，得

$$-g^{\mu\nu}p^2 + \left(1 - \frac{1}{\xi}\right)p^\mu p^\nu, \tag{15}$$

它的逆矩阵是

$$-\frac{1}{p^2}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}(1 - \xi)\right], \tag{16}$$

这是因为

$$\begin{aligned}
&-\frac{1}{p^2}\left[g_{\rho\mu} - \frac{p_\rho p_\mu}{p^2}(1 - \xi)\right]\left[-g^{\mu\nu}p^2 + \left(1 - \frac{1}{\xi}\right)p^\mu p^\nu\right] \\
&= \delta_\rho^\nu - \frac{p_\rho p^\nu}{p^2}\left(1 - \frac{1}{\xi}\right) - \frac{p_\rho p^\nu}{p^2}(1 - \xi) + \frac{p_\rho p^\nu}{p^2}(1 - \xi)\left(1 - \frac{1}{\xi}\right) = \delta_\rho^\nu. \tag{17}
\end{aligned}$$

从而，胶子传播子的形式为

$$\frac{-i\delta^{ab}}{p^2 + i\varepsilon}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}(1 - \xi)\right]. \tag{18}$$

SU(3)$_\text{C}$ 规范变换为

$$q \to Uq, \quad G_\mu^a t^a \to UG_\mu^a t^a U^\dagger + \frac{i}{g_\text{s}}U\partial_\mu U^\dagger, \tag{19}$$

其中 $U(x) = \exp[i\alpha^a(x)t^a]$。胶子场的无穷小规范变换形式是

$$\begin{aligned}
G_\mu^a t^a &\to (1 + i\alpha^a t^a)G_\mu^b t^b(1 - i\alpha^c t^c) + \frac{i}{g_\text{s}}(1 + i\alpha^a t^a)\partial_\mu(1 - i\alpha^c t^c) \\
&= G_\mu^b t^b + i\alpha^a G_\mu^b[t^a, t^b] + \frac{1}{g_\text{s}}(\partial_\mu\alpha^c)t^c + \mathcal{O}(\alpha^2) = G_\mu^a t^a - f^{abc}\alpha^a G_\mu^b t^c + \frac{1}{g_\text{s}}(\partial_\mu\alpha^a)t^a + \mathcal{O}(\alpha^2) \\
&= \left(G_\mu^a + f^{abc}G_\mu^b\alpha^c + \frac{1}{g_\text{s}}\partial_\mu\alpha^a\right)t^a + \mathcal{O}(\alpha^2), \tag{20}
\end{aligned}$$

即

$$\delta G_\mu^a = \frac{1}{g_\text{s}}\partial_\mu\alpha^a + f^{abc}G_\mu^b\alpha^c = \left(\frac{1}{g_\text{s}}\delta^{ac}\partial_\mu + f^{abc}G_\mu^b\right)\alpha^c, \tag{21}$$

因而规范固定函数 G^a 的无穷小规范变换为

$$\delta G^a = \partial^\mu\delta G_\mu^a = \frac{1}{g_\text{s}}\delta^{ac}\partial^2\alpha^c + f^{abc}\partial^\mu G_\mu^b\alpha^c, \quad g_\text{s}\frac{\delta G^a}{\delta\alpha^c} = \delta^{ab}\partial^2 + g_\text{s}f^{abc}\partial^\mu G_\mu^b. \tag{22}$$

Faddeev-Popov 鬼场的拉氏量是

$$\mathcal{L}_{\text{QCD,FP}} = -\bar{\eta}_g^a \left(g_s \frac{\delta G^a}{\delta \alpha^c} \right) \eta_g^c = -\bar{\eta}_g^a (\delta^{ac} \partial^2 + g_s f^{abc} \partial^\mu G_\mu^b) \eta_g^c \rightarrow -\bar{\eta}_g^a \delta^{ab} \partial^2 \eta_g^b + g_s f^{abc} (\partial^\mu \bar{\eta}_g^a) G_\mu^b \eta_g^c. \quad (23)$$

下面列出 QCD 费曼规则。

QCD 顶点:

$$= i g_s \gamma^\mu t^a$$

$$= g_s f^{abc} [g^{\mu\nu}(k-p)^\rho + g^{\nu\rho}(p-q)^\mu + g^{\rho\mu}(q-k)^\nu]$$

$$= -i g_s^2 [f^{abe} f^{cde}(g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho}) + f^{ace} f^{bde}(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\sigma} g^{\nu\rho})$$
$$+ f^{ade} f^{bce}(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma})]$$

$$= -g_s f^{abc} p^\mu$$

胶子传播子:

$$G_\mu^a \quad G_\nu^b = \frac{-i\delta^{ab}}{p^2 + i\varepsilon} \left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}(1-\xi) \right]$$

鬼粒子传播子:

$$\eta_g^a \quad \eta_g^b = \frac{i\delta^{ab}}{p^2 + i\varepsilon}$$

4 费米子电弱规范相互作用拉氏量和费曼规则

表 1 列出标准模型费米子场的量子数电荷数 Q、弱同位旋第 3 分量 T^3、弱超荷 Y、重子数 B 和轻子数 $L_e/L_\mu/L_\tau$。每代左手费米子场构成 2 个 $\mathrm{SU}(2)_\mathrm{L}$ 二重态

$$L_{i\mathrm{L}} = \begin{pmatrix} P_\mathrm{L}\nu_i \\ P_\mathrm{L}\ell_i \end{pmatrix} = \begin{pmatrix} \nu_{i\mathrm{L}} \\ \ell_{i\mathrm{L}} \end{pmatrix}, \quad Q_{i\mathrm{L}} = \begin{pmatrix} P_\mathrm{L}u_i \\ P_\mathrm{L}d'_i \end{pmatrix} = \begin{pmatrix} u_{i\mathrm{L}} \\ d'_{i\mathrm{L}} \end{pmatrix}, \quad i = 1, 2, 3. \tag{24}$$

下型夸克的质量本征态 d_j 与规范本征态 d'_j 通过 Cabibbo-Kobayashi-Maskawa (CKM) 矩阵 V_{ij} 联系起来:

$$d'_i = V_{ij}d_j. \tag{25}$$

右手费米子场 $\ell_{i\mathrm{R}} = P_\mathrm{R}\ell_i$、$u_{i\mathrm{R}} = P_\mathrm{R}u_i$ 和 $d'_{i\mathrm{R}} = P_\mathrm{R}d'_i$ 是 $\mathrm{SU}(2)_\mathrm{L}$ 单态。它们的电荷数 Q、弱同位旋第 3 分量 T^3 和弱超荷 Y 满足关系

$$Q = T^3 + Y. \tag{26}$$

表 1: 标准模型费米子场的量子数。

统一记号	第一代	第二代	第三代	Q	T^3	Y	B	$L_e/L_\mu/L_\tau$
$L_{i\mathrm{L}} = \begin{pmatrix} \nu_{i\mathrm{L}} \\ \ell_{i\mathrm{L}} \end{pmatrix}$	$\begin{pmatrix} \nu_{e\mathrm{L}} \\ e_\mathrm{L} \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu\mathrm{L}} \\ \mu_\mathrm{L} \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau\mathrm{L}} \\ \tau_\mathrm{L} \end{pmatrix}$	0 -1	$1/2$ $-1/2$	$-1/2$ $-1/2$	0 0	1 1
$Q_{i\mathrm{L}} = \begin{pmatrix} u_{i\mathrm{L}} \\ d'_{i\mathrm{L}} \end{pmatrix}$	$\begin{pmatrix} u_\mathrm{L} \\ d'_\mathrm{L} \end{pmatrix}$	$\begin{pmatrix} c_\mathrm{L} \\ s'_\mathrm{L} \end{pmatrix}$	$\begin{pmatrix} t_\mathrm{L} \\ b'_\mathrm{L} \end{pmatrix}$	$2/3$ $-1/3$	$1/2$ $-1/2$	$1/6$ $1/6$	$1/3$ $1/3$	0 0
$\ell_{i\mathrm{R}}$	e_R	μ_R	τ_R	-1	0	-1	0	1
$u_{i\mathrm{R}}$	u_R	c_R	t_R	$2/3$	0	$2/3$	$1/3$	0
$d'_{i\mathrm{R}}$	d'_R	s'_R	b'_R	$-1/3$	0	$-1/3$	$1/3$	0

$\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ 规范不变的费米子协变动能项为

$$\mathcal{L}_\mathrm{EWF} = \bar{Q}_{i\mathrm{L}}i\slashed{D}Q_{i\mathrm{L}} + \bar{u}_{i\mathrm{R}}i\slashed{D}u_{i\mathrm{R}} + \bar{d}'_{i\mathrm{R}}i\slashed{D}d'_{i\mathrm{R}} + \bar{L}_{i\mathrm{L}}i\slashed{D}L_{i\mathrm{L}} + \bar{\ell}_{i\mathrm{R}}i\slashed{D}\ell_{i\mathrm{R}}. \tag{27}$$

对于 $\mathrm{SU}(2)_\mathrm{L}$ 二重态 $Q_{i\mathrm{L}}$ 和 $L_{i\mathrm{L}}$,协变导数为

$$D_\mu = \partial_\mu - ig'B_\mu Y - igW_\mu^a\tau^a, \quad \tau^a = \frac{\sigma^a}{2}. \tag{28}$$

弱同位旋第 3 分量 T^3 是生成元 τ^3 的本征值。对于 $\mathrm{SU}(2)_\mathrm{L}$ 单态 $u_{i\mathrm{R}}$、$d'_{i\mathrm{R}}$ 和 $\ell_{i\mathrm{R}}$,协变导数为

$$D_\mu = \partial_\mu - ig'B_\mu Y. \tag{29}$$

规范场 $W_\mu^a(x)$ 和 $B_\mu(x)$ 跟左手费米子的相互作用与右手费米子场不同,而在 QED 中,电磁场 $A_\mu(x)$ 跟左手费米子的相互作用却与右手费米子场相同。为了回到 QED 的情况,需要把 $W_\mu^3(x)$ 和 $B_\mu(x)$ 混

合起来，得到电磁场 $A_\mu(x)$ 和另一个中性规范场 $Z_\mu(x)$，即定义

$$A_\mu \equiv \frac{1}{\sqrt{g^2 + g'^2}}(g'W_\mu^3 + gB_\mu) = s_{\mathrm{W}}W_\mu^3 + c_{\mathrm{W}}B_\mu, \tag{30}$$

$$Z_\mu \equiv \frac{1}{\sqrt{g^2 + g'^2}}(gW_\mu^3 - g'B_\mu) = c_{\mathrm{W}}W_\mu^3 - s_{\mathrm{W}}B_\mu, \tag{31}$$

$$W_\mu^\pm \equiv \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2), \tag{32}$$

或

$$B_\mu = c_{\mathrm{W}}A_\mu - s_{\mathrm{W}}Z_\mu, \quad W_\mu^3 = s_{\mathrm{W}}A_\mu + c_{\mathrm{W}}Z_\mu, \tag{33}$$

$$W_\mu^1 = \frac{1}{\sqrt{2}}(W_\mu^+ + W_\mu^-), \quad W_\mu^2 = \frac{i}{\sqrt{2}}(W_\mu^+ - W_\mu^-). \tag{34}$$

参数间有如下关系，

$$s_{\mathrm{W}} \equiv \sin\theta_{\mathrm{W}} = \frac{g'}{\sqrt{g^2 + g'^2}}, \quad c_{\mathrm{W}} \equiv \cos\theta_{\mathrm{W}} = \frac{g}{\sqrt{g^2 + g'^2}}, \quad e \equiv \frac{gg'}{\sqrt{g^2 + g'^2}} = gs_{\mathrm{W}} = g'c_{\mathrm{W}}. \tag{35}$$

这里 θ_{W} 称为 Weinberg 角。

利用

$$\begin{aligned}
g'YB_\mu + gT^3W_\mu^3 &= g'Y(c_{\mathrm{W}}A_\mu - s_{\mathrm{W}}Z_\mu) + gT^3(s_{\mathrm{W}}A_\mu + c_{\mathrm{W}}Z_\mu) \\
&= e(Y + T^3)A_\mu + \left(gc_{\mathrm{W}}T^3 - \frac{gs_{\mathrm{W}}}{c_{\mathrm{W}}}s_{\mathrm{W}}Y\right)Z_\mu = QeA_\mu + \frac{g}{c_{\mathrm{W}}}(T^3c_{\mathrm{W}}^2 - Ys_{\mathrm{W}}^2)Z_\mu \\
&= QeA_\mu + \frac{g}{c_{\mathrm{W}}}(T^3 - Qs_{\mathrm{W}}^2)Z_\mu,
\end{aligned} \tag{36}$$

有

$$\begin{aligned}
D_\mu Q_{i\mathrm{L}} &= (\partial_\mu - ig'B_\mu Y - igW_\mu^a\tau^a)Q_{i\mathrm{L}} = \partial_\mu Q_{i\mathrm{L}} - i\begin{pmatrix} g'YB_\mu + gT^3W_\mu^3 & \frac{1}{2}g(W_\mu^1 - iW_\mu^2) \\ \frac{1}{2}g(W_\mu^1 + iW_\mu^2) & g'YB_\mu + gT^3W_\mu^3 \end{pmatrix}Q_{i\mathrm{L}} \\
&= \partial_\mu Q_{i\mathrm{L}} - i\begin{pmatrix} QeA_\mu + \frac{g}{c_{\mathrm{W}}}(T^3 - Qs_{\mathrm{W}}^2)Z_\mu & \frac{1}{\sqrt{2}}gW_\mu^+ \\ \frac{1}{\sqrt{2}}gW_\mu^- & QeA_\mu + \frac{g}{c_{\mathrm{W}}}(T^3 - Qs_{\mathrm{W}}^2)Z_\mu \end{pmatrix}Q_{i\mathrm{L}} \\
&= \partial_\mu Q_{i\mathrm{L}} - i\begin{pmatrix} \left[QeA_\mu + \frac{g}{c_{\mathrm{W}}}(T^3 - Qs_{\mathrm{W}}^2)Z_\mu\right]u_{i\mathrm{L}} + \frac{1}{\sqrt{2}}gW_\mu^+ d'_{i\mathrm{L}} \\ \frac{1}{\sqrt{2}}gW_\mu^- u_{i\mathrm{L}} + \left[QeA_\mu + \frac{g}{c_{\mathrm{W}}}(T^3 - Qs_{\mathrm{W}}^2)\right]d'_{i\mathrm{L}} \end{pmatrix},
\end{aligned} \tag{37}$$

故

$$\begin{aligned}
\bar{Q}_{i\mathrm{L}}i\slashed{D}Q_{i\mathrm{L}} &\supset \left[QeA_\mu + \frac{g}{c_{\mathrm{W}}}(T^3 - Qs_{\mathrm{W}}^2)Z_\mu\right]\bar{u}_{i\mathrm{L}}\gamma^\mu u_{i\mathrm{L}} + \left[QeA_\mu + \frac{g}{c_{\mathrm{W}}}(T^3 - Qs_{\mathrm{W}}^2)Z_\mu\right]\bar{d}'_{i\mathrm{L}}\gamma^\mu d'_{i\mathrm{L}} \\
&\quad + \frac{1}{\sqrt{2}}gW_\mu^+\bar{u}_{i\mathrm{L}}\gamma^\mu d'_{i\mathrm{L}} + \frac{1}{\sqrt{2}}gW_\mu^-\bar{d}'_{i\mathrm{L}}\gamma^\mu u_{i\mathrm{L}}
\end{aligned}$$

$$= \left(QeA_\mu + \frac{g}{c_W} g_L Z_\mu \right) \bar{u}_i \gamma^\mu \frac{1-\gamma_5}{2} u_i + \left(QeA_\mu + \frac{g}{c_W} g_L Z_\mu \right) \bar{d}_i \gamma^\mu \frac{1-\gamma_5}{2} d_i$$
$$+ \frac{1}{\sqrt{2}} g W_\mu^+ \bar{u}_i \gamma^\mu \frac{1-\gamma_5}{2} V_{ij} d_j + \frac{1}{\sqrt{2}} g W_\mu^- \bar{d}_j V_{ji}^\dagger \gamma^\mu \frac{1-\gamma_5}{2} u_i, \tag{38}$$

其中

$$g_L \equiv T^3 - Q s_W^2. \tag{39}$$

另一方面,

$$D_\mu d'_{iR} = (\partial_\mu - ig' B_\mu Y) d'_{iR} = \partial_\mu d'_{iR} - ig'Q(c_W A_\mu - s_W Z_\mu)d'_{iR} = \partial_\mu d'_{iR} - iQeA_\mu d'_{iR} + i\frac{g}{c_W} Q s_W^2 Z_\mu d'_{iR}, \tag{40}$$

则

$$\bar{u}_{iR} i \slashed{D} u_{iR} + \bar{d}'_{iR} i \slashed{D} d'_{iR} \supset \left(QeA_\mu - \frac{g}{c_W} Q s_W^2 Z_\mu \right) \bar{u}_{iR} \gamma^\mu u_{iR} + \left(QeA_\mu - \frac{g}{c_W} Q s_W^2 Z_\mu \right) \bar{d}'_{iR} \gamma^\mu d'_{iR}$$
$$= \left(QeA_\mu + \frac{g}{c_W} g_R Z_\mu \right) \bar{u}_i \gamma^\mu \frac{1+\gamma_5}{2} u_i + \left(QeA_\mu + \frac{g}{c_W} g_R Z_\mu \right) \bar{d}_i \gamma^\mu \frac{1+\gamma_5}{2} d_i, \tag{41}$$

其中

$$g_R \equiv -Q s_W^2. \tag{42}$$

定义

$$g_V \equiv g_L + g_R = T^3 - 2Q s_W^2, \quad g_A \equiv g_L - g_R = T^3, \tag{43}$$

可得

$$\bar{Q}_{iL} i \slashed{D} Q_{iL} + \bar{u}_{iR} i \slashed{D} u_{iR} + \bar{d}'_{iR} i \slashed{D} d'_{iR}$$
$$\supset Qe\bar{u}_i \gamma^\mu u_i A_\mu + Qe\bar{d}\gamma^\mu d_i A_\mu + \frac{g}{2c_W} \bar{u}_i \gamma^\mu (g_V - g_A \gamma_5) u_i Z_\mu + \frac{g}{2c_W} \bar{d}_i \gamma^\mu (g_V - g_A \gamma_5) d_i Z_\mu$$
$$+ \frac{1}{\sqrt{2}} g W_\mu^+ \bar{u}_i \gamma^\mu P_L V_{ij} d_j + \frac{1}{\sqrt{2}} g W_\mu^- \bar{d}_j V_{ji}^\dagger \gamma^\mu P_L u_i. \tag{44}$$

同理,有

$$\bar{L}_{iL} i \slashed{D} L_{iL} + \bar{\ell}_{iR} i \slashed{D} \ell_{iR} \supset Qe\bar{\ell}_i \gamma^\mu \ell_i A_\mu + \frac{g}{2c_W} \bar{\ell}_i \gamma^\mu (g_V - g_A \gamma_5) \ell_i Z_\mu + \frac{g}{2c_W} \bar{\nu}_i \gamma^\mu (g_V - g_A \gamma_5) \nu_i Z_\mu$$
$$+ \frac{1}{\sqrt{2}} g W_\mu^+ \bar{\nu}_i \gamma^\mu P_L \ell_i + \frac{1}{\sqrt{2}} g W_\mu^- \bar{\ell}_i \gamma^\mu P_L \nu_i. \tag{45}$$

总结起来,可以写成流耦合的形式,

$$\mathcal{L}_{EWF} \supset \sum_f \left[Q_f e \bar{f} \gamma^\mu f A_\mu + \frac{g}{2c_W} \bar{f} \gamma^\mu (g_V^f - g_A^f \gamma_5) f Z_\mu \right] + g(W_\mu^+ J_W^{+\mu} + W_\mu^- J_W^{-\mu})$$
$$= eA_\mu J_{EM}^\mu + g(Z_\mu J_Z^\mu + W_\mu^+ J_W^{+\mu} + W_\mu^- J_W^{-\mu}), \tag{46}$$

其中，流的定义为

$$J_{\text{EM}}^{\mu} \equiv \sum_f Q_f \bar{f} \gamma^{\mu} f, \quad J_Z^{\mu} \equiv \frac{1}{2c_W} \sum_f \bar{f} \gamma^{\mu} (g_V^f - g_A^f \gamma_5) f = \frac{1}{c_W} \sum_f (g_L^f \bar{f}_L \gamma^{\mu} f_L + g_R^f \bar{f}_R \gamma^{\mu} f_R),$$

$$J_W^{+\mu} \equiv \frac{1}{\sqrt{2}} (\bar{u}_{iL} \gamma^{\mu} V_{ij} d_{jL} + \bar{\nu}_{iL} \gamma^{\mu} \ell_{iL}), \quad J_W^{-\mu} \equiv \frac{1}{\sqrt{2}} (\bar{d}_{jL} V_{ji}^{\dagger} \gamma^{\mu} u_{iL} + \bar{\ell}_{iL} \gamma^{\mu} \nu_{iL}). \tag{47}$$

对于各种费米子，相关系数如下，

$$Q_{u_i} = \frac{2}{3}, \quad Q_{d_i} = -\frac{1}{3}, \quad Q_{\nu_i} = 0, \quad Q_{\ell_i} = -1; \tag{48}$$

$$g_V^{u_i} = \frac{1}{2} - \frac{4}{3} s_W^2, \quad g_A^{u_i} = \frac{1}{2}; \quad g_V^{d_i} = -\frac{1}{2} + \frac{2}{3} s_W^2, \quad g_A^{d_i} = -\frac{1}{2}; \tag{49}$$
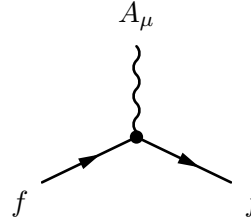
$$g_V^{\nu_i} = \frac{1}{2}, \quad g_A^{\nu_i} = \frac{1}{2}; \quad g_V^{\ell_i} = -\frac{1}{2} + 2 s_W^2, \quad g_A^{\ell_i} = -\frac{1}{2}; \tag{50}$$

$$g_L^{u_i} = \frac{1}{2} - \frac{2}{3} s_W^2, \quad g_R^{u_i} = -\frac{2}{3} s_W^2; \quad g_L^{d_i} = -\frac{1}{2} + \frac{1}{3} s_W^2, \quad g_R^{d_i} = \frac{1}{3} s_W^2; \tag{51}$$

$$g_L^{\nu_i} = \frac{1}{2}, \quad g_R^{\nu_i} = 0; \quad g_L^{\ell_i} = -\frac{1}{2} + s_W^2, \quad g_R^{\ell_i} = s_W^2. \tag{52}$$
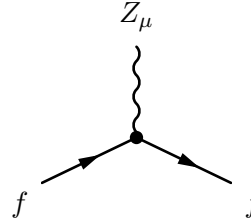
下面给出费米子电弱规范相互作用顶点的费曼规则。

QED 顶点：

$$= iQ_f e \gamma^{\mu} \quad (\text{对于电子}, \ Q_e = -1)$$

费米子与 Z 玻色子的耦合：
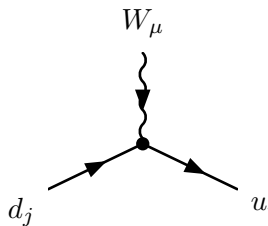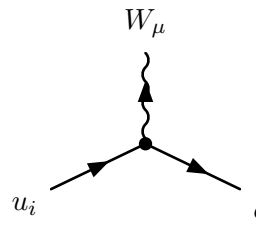
$$= i \frac{g}{2c_W} \gamma^{\mu} (g_V^f - g_A^f \gamma_5)$$

$$g_V^{u_i} = \frac{1}{2} - \frac{4}{3} s_W^2, \quad g_A^{u_i} = \frac{1}{2}; \quad g_V^{d_i} = -\frac{1}{2} + \frac{2}{3} s_W^2, \quad g_A^{d_i} = -\frac{1}{2};$$

$$g_V^{\nu_i} = \frac{1}{2}, \quad g_A^{\nu_i} = \frac{1}{2}; \quad g_V^{\ell_i} = -\frac{1}{2} + 2 s_W^2, \quad g_A^{\ell_i} = -\frac{1}{2}.$$

费米子与 $W^{\pm}$ 玻色子的耦合：

$$= i \frac{g}{\sqrt{2}} V_{ij} \gamma^{\mu} P_L$$

$$= i \frac{g}{\sqrt{2}} V_{ji}^{\dagger} \gamma^{\mu} P_L$$

$$W_\mu \qquad = i\frac{g}{\sqrt{2}}\gamma^\mu P_{\mathrm{L}} \qquad\qquad W_\mu \qquad = i\frac{g}{\sqrt{2}}\gamma^\mu P_{\mathrm{L}}$$

5 电弱规范场自相互作用拉氏量和费曼规则

电弱规范场自相互作用拉氏量是

$$\mathcal{L}_{\mathrm{EWG}} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}, \tag{53}$$

其中

$$W^{a\mu\nu} \equiv \partial^\mu W^{a\nu} - \partial^\nu W^{a\mu} + g\varepsilon^{abc}W^{b\mu}W^{c\nu}, \quad B^{\mu\nu} \equiv \partial^\mu B^\nu - \partial^\nu B^\mu. \tag{54}$$

利用 (33) 式和 (34) 式，可得

$$\begin{aligned}
&W_\mu^2 W_\nu^3 - W_\mu^3 W_\nu^2 \\
&= \frac{i}{\sqrt{2}}[(W_\mu^+ - W_\mu^-)(s_{\mathrm{W}}A_\nu + c_{\mathrm{W}}Z_\nu) - (s_{\mathrm{W}}A_\mu + c_{\mathrm{W}}Z_\mu)(W_\nu^+ - W_\nu^-)] \\
&= \frac{i}{\sqrt{2}}[s_{\mathrm{W}}(W_\mu^+ A_\nu - A_\mu W_\nu^+) + c_{\mathrm{W}}(W_\mu^+ Z_\nu - Z_\mu W_\nu^+) - s_{\mathrm{W}}(W_\mu^- A_\nu - A_\mu W_\nu^-) - c_{\mathrm{W}}(W_\mu^- Z_\nu - Z_\mu W_\nu^-)],
\end{aligned} \tag{55}$$

$$\begin{aligned}
&W_\mu^3 W_\nu^1 - W_\mu^1 W_\nu^3 \\
&= \frac{1}{\sqrt{2}}[(s_{\mathrm{W}}A_\mu + c_{\mathrm{W}}Z_\mu)(W_\nu^+ + W_\nu^-) - (W_\mu^+ + W_\mu^-)(s_{\mathrm{W}}A_\nu + c_{\mathrm{W}}Z_\nu)] \\
&= -\frac{1}{\sqrt{2}}[s_{\mathrm{W}}(W_\mu^+ A_\nu - A_\mu W_\nu^+) + c_{\mathrm{W}}(W_\mu^+ Z_\nu - Z_\mu W_\nu^+) + s_{\mathrm{W}}(W_\mu^- A_\nu - A_\mu W_\nu^-) + c_{\mathrm{W}}(W_\mu^- Z_\nu - Z_\mu W_\nu^-)].
\end{aligned} \tag{56}$$

从而，

$$\begin{aligned}
W_{\mu\nu}^1 &= \partial_\mu W_\nu^1 - \partial_\nu W_\mu^1 + g\varepsilon^{1bc}W_\mu^b W_\nu^c = \partial_\mu W_\nu^1 - \partial_\nu W_\mu^1 + gW_\mu^2 W_\nu^3 - gW_\mu^3 W_\nu^2 \\
&= \frac{1}{\sqrt{2}}(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+) + \frac{1}{\sqrt{2}}(\partial_\mu W_\nu^- - \partial_\nu W_\mu^-) + g(W_\mu^2 W_\nu^3 - gW_\mu^3 W_\nu^2) \\
&= \frac{1}{\sqrt{2}}\{\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ + ig[s_{\mathrm{W}}(W_\mu^+ A_\nu - A_\mu W_\nu^+) + c_{\mathrm{W}}(W_\mu^+ Z_\nu - Z_\mu W_\nu^+)]\} \\
&\quad + \frac{1}{\sqrt{2}}\{\partial_\mu W_\nu^- - \partial_\nu W_\mu^- - ig[s_{\mathrm{W}}(W_\mu^- A_\nu - A_\mu W_\nu^-) + c_{\mathrm{W}}(W_\mu^- Z_\nu - Z_\mu W_\nu^-)]\} \\
&= \frac{1}{\sqrt{2}}(F_{\mu\nu}^+ + F_{\mu\nu}^-),
\end{aligned} \tag{57}$$

其中，

$$F_{\mu\nu}^+ \equiv \partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ + ie(W_\mu^+ A_\nu - A_\mu W_\nu^+) + igc_{\mathrm{W}}(W_\mu^+ Z_\nu - Z_\mu W_\nu^+), \tag{58}$$

$$F_{\mu\nu}^- \equiv \partial_\mu W_\nu^- - \partial_\nu W_\mu^- - ie(W_\mu^- A_\nu - A_\mu W_\nu^-) - igc_{\mathrm{W}}(W_\mu^- Z_\nu - Z_\mu W_\nu^-). \tag{59}$$

另一方面,

$$
\begin{aligned}
W_{\mu\nu}^2 &= \partial_\mu W_\nu^2 - \partial_\nu W_\mu^2 + g\varepsilon^{2bc}W_\mu^b W_\nu^c = \partial_\mu W_\nu^2 - \partial_\nu W_\mu^2 - gW_\mu^1 W_\nu^3 + gW_\mu^3 W_\nu^1 \\
&= \frac{i}{\sqrt{2}}(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+) - \frac{i}{\sqrt{2}}(\partial_\mu W_\nu^- - \partial_\nu W_\mu^-) + g(W_\mu^3 W_\nu^1 - W_\mu^1 W_\nu^3) \\
&= \frac{i}{\sqrt{2}}\{\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ + ig[s_{\mathrm{W}}(W_\mu^+ A_\nu - A_\mu W_\nu^+) + c_{\mathrm{W}}(W_\mu^+ Z_\nu - Z_\mu W_\nu^+)]\} \\
&\quad - \frac{i}{\sqrt{2}}\{\partial_\mu W_\nu^- - \partial_\nu W_\mu^- - ig[s_{\mathrm{W}}(W_\mu^- A_\nu - A_\mu W_\nu^-) + c_{\mathrm{W}}(W_\mu^- Z_\nu - Z_\mu W_\nu^-)]\} \\
&= \frac{i}{\sqrt{2}}(F_{\mu\nu}^+ - F_{\mu\nu}^-).
\end{aligned}
\tag{60}
$$

因此,

$$
\begin{aligned}
&-\frac{1}{4}W_{\mu\nu}^1 W^{1\mu\nu} - \frac{1}{4}W_{\mu\nu}^2 W^{2\mu\nu} \\
&= -\frac{1}{8}(F_{\mu\nu}^+ + F_{\mu\nu}^-)(F^{+\mu\nu} + F^{-\mu\nu}) + \frac{1}{8}(F_{\mu\nu}^+ - F_{\mu\nu}^-)(F^{+\mu\nu} - F^{-\mu\nu}) = -\frac{1}{2}F_{\mu\nu}^+ F^{-\mu\nu} \\
&= -\frac{1}{2}[\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ + ie(W_\mu^+ A_\nu - A_\mu W_\nu^+) + igc_{\mathrm{W}}(W_\mu^+ Z_\nu - Z_\mu W_\nu^+)] \\
&\quad \times [\partial^\mu W^{-\nu} - \partial^\nu W^{-\mu} - ie(W^{-\mu}A^\nu - A^\mu W^{-\nu}) - igc_{\mathrm{W}}(W^{-\mu}Z^\nu - Z^\mu W^{-\nu})] \\
&= -(\partial_\mu W_\nu^+)(\partial^\mu W^{-\nu}) + (\partial_\mu W_\nu^+)(\partial^\nu W^{-\mu}) \\
&\quad + ie[(\partial_\mu W_\nu^+)W^{-\mu}A^\nu - (\partial_\mu W_\nu^+)W^{-\nu}A^\mu - W_\mu^+(\partial^\mu W^{-\nu})A_\nu + W_\nu^+(\partial^\mu W^{-\nu})A_\mu] \\
&\quad + igc_{\mathrm{W}}[(\partial_\mu W_\nu^+)W^{-\mu}Z^\nu - (\partial_\mu W_\nu^+)W^{-\nu}Z^\mu - W_\mu^+(\partial^\mu W^{-\nu})Z_\nu + W_\nu^+(\partial^\mu W^{-\nu})Z_\mu] \\
&\quad + e^2(W_\mu^+ W^{-\nu}A_\nu A^\mu - W_\mu^+ W^{-\mu}A_\nu A^\nu) + g^2 c_{\mathrm{W}}^2(W_\mu^+ W^{-\nu}Z_\nu Z^\mu - W_\mu^+ W^{-\mu}Z_\nu Z^\nu) \\
&\quad + egc_{\mathrm{W}}(W_\mu^+ W^{-\nu}A_\nu Z^\mu + W_\mu^+ W^{-\nu}A^\mu Z_\nu - 2W_\mu^+ W^{-\mu}A_\nu Z^\nu).
\end{aligned}
\tag{61}
$$

由

$$
W_\mu^1 W_\nu^2 - W_\mu^2 W_\nu^1 = \frac{i}{2}(W_\mu^+ + W_\mu^-)(W_\nu^+ - W_\nu^-) - \frac{i}{2}(W_\mu^+ - W_\mu^-)(W_\nu^+ + W_\nu^-) = -i(W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+),
\tag{62}
$$

可得

$$
\begin{aligned}
W_{\mu\nu}^3 &= \partial_\mu W_\nu^3 - \partial_\nu W_\mu^3 + g\varepsilon^{3bc}W_\mu^b W_\nu^c = \partial_\mu W_\nu^3 - \partial_\nu W_\mu^3 + gW_\mu^1 W_\nu^2 - gW_\mu^2 W_\nu^1 \\
&= s_{\mathrm{W}}\partial_\mu A_\nu + c_{\mathrm{W}}\partial_\mu Z_\nu - s_{\mathrm{W}}\partial_\nu A_\mu + c_{\mathrm{W}}\partial_\nu Z_\mu + g(W_\mu^1 W_\nu^2 - W_\mu^2 W_\nu^1) \\
&= s_{\mathrm{W}}(\partial_\mu A_\nu - \partial_\nu A_\mu) + c_{\mathrm{W}}(\partial_\mu Z_\nu - \partial_\nu Z_\mu) - ig(W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+),
\end{aligned}
\tag{63}
$$

$$
B_{\mu\nu} = \partial_\mu(c_{\mathrm{W}}A_\nu - s_{\mathrm{W}}Z_\nu) - \partial_\nu(c_{\mathrm{W}}A_\mu - s_{\mathrm{W}}Z_\mu) = c_{\mathrm{W}}(\partial_\mu A_\nu - \partial_\nu A_\mu) - s_{\mathrm{W}}(\partial_\mu Z_\nu - \partial_\nu Z_\mu).
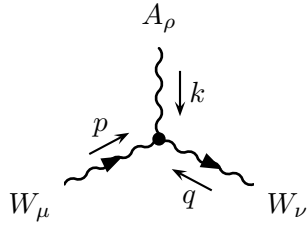\tag{64}
$$

于是,

$$
\begin{aligned}
&-\frac{1}{4}W_{\mu\nu}^3 W^{3\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
&= -\frac{1}{2}[(\partial_\mu A_\nu)(\partial^\mu A^\nu) - (\partial_\mu A_\nu)(\partial^\nu A^\mu)] - \frac{1}{2}[(\partial_\mu Z_\nu)(\partial^\mu Z^\nu) - (\partial_\mu Z_\nu)(\partial^\nu Z^\mu)] \\
&\quad + ie[W^{+\mu}W^{-\nu}(\partial_\mu A_\nu) - W^{+\nu}W^{-\mu}(\partial_\mu A_\nu)] + igc_{\mathrm{W}}[W^{+\mu}W^{-\nu}(\partial_\mu Z_\nu) - W^{+\nu}W^{-\mu}(\partial_\mu Z_\nu)] \\
&\quad + \frac{1}{2}g^2(W_\mu^+ W^{+\mu}W_\nu^- W^{-\nu} - W_\mu^+ W^{+\nu}W_\nu^- W^{-\mu}).
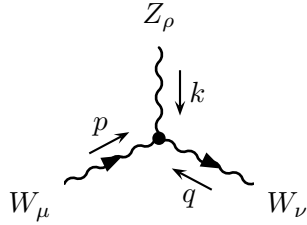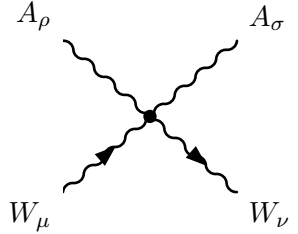\end{aligned}
\tag{65}
$$

综合起来，有

$$\mathcal{L}_{\text{EWG}} = \frac{1}{2}[(\partial_\mu A_\nu)(\partial^\nu A^\mu) - (\partial_\mu A_\nu)(\partial^\mu A^\nu)] + \frac{1}{2}[(\partial_\mu Z_\nu)(\partial^\nu Z^\mu) - (\partial_\mu Z_\nu)(\partial^\mu Z^\nu)]$$
$$+ (\partial_\mu W_\nu^+)(\partial^\nu W^{-\mu}) - (\partial_\mu W_\nu^+)(\partial^\mu W^{-\nu}) + \frac{1}{2}g^2(W_\mu^+ W^{+\mu} W_\nu^- W^{-\nu} - W_\mu^+ W^{+\nu} W_\nu^- W^{-\mu})$$
$$+ ie[(\partial_\mu W_\nu^+)W^{-\mu}A^\nu - (\partial_\mu W_\nu^+)W^{-\nu}A^\mu - W^{+\mu}(\partial_\mu W_\nu^-)A^\nu + W^{+\nu}(\partial_\mu W_\nu^-)A^\mu$$
$$+ W^{+\mu}W^{-\nu}(\partial_\mu A_\nu) - W^{+\nu}W^{-\mu}(\partial_\mu A_\nu)] + e^2(W_\mu^+ W^{-\nu}A_\nu A^\mu - W_\mu^+ W^{-\mu}A_\nu A^\nu)$$
$$+ igc_{\text{W}}[(\partial_\mu W_\nu^+)W^{-\mu}Z^\nu - (\partial_\mu W_\nu^+)W^{-\nu}Z^\mu - W^{+\mu}(\partial_\mu W_\nu^-)Z^\nu + W^{+\nu}(\partial_\mu W_\nu^-)Z^\mu$$
$$+ W^{+\mu}W^{-\nu}(\partial_\mu Z_\nu) - W^{+\nu}W^{-\mu}(\partial_\mu Z_\nu)] + g^2 c_{\text{W}}^2(W_\mu^+ W^{-\nu}Z_\nu Z^\mu - W_\mu^+ W^{-\mu}Z_\nu Z^\nu)$$
$$+ egc_{\text{W}}(W_\mu^+ W^{-\nu}A_\nu Z^\mu + W_\mu^+ W^{-\nu}A^\mu Z_\nu - 2W_\mu^+ W^{-\mu}A_\nu Z^\nu). \tag{66}$$

下面是电弱规范玻色子自耦合的费曼规则：
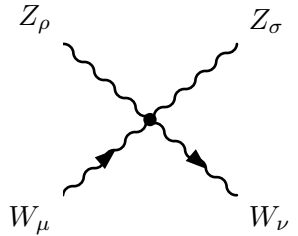
$$= -ie[(g^{\mu\nu}(p-q)^\rho + g^{\nu\rho}(q-k)^\mu + g^{\rho\mu}(k-p)^\nu]$$
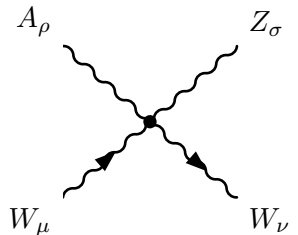
$$= -igc_{\text{W}}[(g^{\mu\nu}(p-q)^\rho + g^{\nu\rho}(q-k)^\mu + g^{\rho\mu}(k-p)^\nu]$$
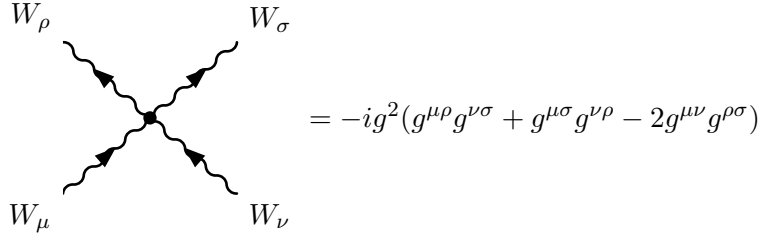
$$= ie^2(g^{\mu\rho}g^{\nu\sigma} + g^{\mu\sigma}g^{\nu\rho} - 2g^{\mu\nu}g^{\rho\sigma})$$

$$= ig^2 c_{\text{W}}^2(g^{\mu\rho}g^{\nu\sigma} + g^{\mu\sigma}g^{\nu\rho} - 2g^{\mu\nu}g^{\rho\sigma})$$

$$= iegc_{\text{W}}(g^{\mu\rho}g^{\nu\sigma} + g^{\mu\sigma}g^{\nu\rho} - 2g^{\mu\nu}g^{\rho\sigma})$$

$$= -ig^2(g^{\mu\rho}g^{\nu\sigma} + g^{\mu\sigma}g^{\nu\rho} - 2g^{\mu\nu}g^{\rho\sigma})$$

6 幺正规范下 Higgs 场相关拉氏量和费曼规则

Higgs 场的协变动能项和势能项为

$$\mathcal{L}_{\mathrm{H}} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - V_{\mathrm{H}}(\Phi), \quad V_{\mathrm{H}}(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2, \tag{67}$$

其中

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}, \quad D_\mu\Phi = (\partial_\mu - ig'B_\mu Y_H - igW_\mu^a\tau^a)\Phi, \quad Y_H = \frac{1}{2}. \tag{68}$$

当 $\lambda > 0$ 且 $\mu^2 > 0$ 时, Higgs 场势能 $V_{\mathrm{H}}(\Phi)$ 呈现出图 1 所示墨西哥草帽状的形式, 势能最小值位于方程

$$\Phi^\dagger\Phi = [\mathrm{Re}(\phi^+)]^2 + [\mathrm{Im}(\phi^+)]^2 + [\mathrm{Re}(\phi^0)]^2 + [\mathrm{Im}(\phi^0)]^2 = \frac{v^2}{2} \tag{69}$$

对应的 4 维球面上, 其中 $v \equiv \sqrt{\mu^2/\lambda}$, 满足

$$\mu^2 = \lambda v^2. \tag{70}$$
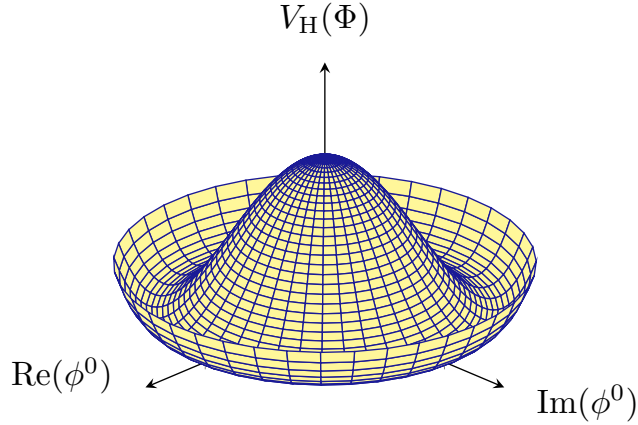
图 1: Higgs 场势能示意图。这里压缩掉 $\mathrm{Re}(\phi^+)$ 和 $\mathrm{Im}(\phi^+)$ 两个维度。

Higgs 场的真空期待值位于这个 4 维球面上的某一点, 不失一般性, 可将它取为

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}. \tag{71}$$

其它真空期待值可通过整体变换

$$\langle\Phi\rangle \to \exp(i\alpha^a\tau^a)\exp(i\alpha^Y Y_H)\langle\Phi\rangle \tag{72}$$

得到，因为 $\langle\Phi^\dagger\Phi\rangle$ 在这样的变换下保持不变。若 $\alpha^1=\alpha^2=0$ 且 $\alpha^3=\alpha^Y$，则 $\langle\Phi\rangle$ 在变换下不变。因此，有 1 个方向的规范对称性没有受到破坏，只有 3 个方向的规范对称性发生自发破缺。根据 Goldstone 定理，破缺后生成 3 个无质量的 Nambu-Goldstone 玻色子。最终，有 3 个规范玻色子自由度通过 Brout–Englert–Higgs 机制获得质量。

以 $\langle\Phi\rangle$ 为基础，将 Higgs 场一般地参数化为

$$\Phi(x) = \exp\left[-i\frac{\chi^a(x)}{v}\tau^a\right]\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H(x) \end{pmatrix}, \tag{73}$$

其中 $\chi^a(x)$ 和 $H(x)$ 都是实标量场。$\exp[-i\chi^a(x)\tau^a/v]$ 因子能够通过 $\mathrm{SU}(2)_\mathrm{L}$ 规范变换消去，因而可将 $\Phi(x)$ 直接取为

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H(x) \end{pmatrix}, \quad \Phi^\dagger\Phi = \frac{1}{2}(v+H)^2. \tag{74}$$

此时 Higgs 场只剩下一个物理自由度 $H(x)$，对应于 Higgs 玻色子，这种取法称为幺正规范。

在幺正规范下，势能项化为

$$\begin{aligned}
-V_\mathrm{H}(\Phi) &= \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 = \frac{1}{2}\mu^2(v+H)^2 - \frac{1}{4}\lambda(v+H)^4 \\
&= \frac{1}{2}\mu^2(v^2+H^2+2vH) - \frac{1}{4}\lambda(v^4+4v^2H^2+H^4+4v^3H+2v^2H^2+4vH^3) \\
&= \frac{1}{4}\mu^2v^2 + \frac{1}{4}(\mu^2-\lambda v^2)v^2 + (\mu^2-\lambda v^2)vH + \frac{1}{2}(\mu^2-\lambda v^2)H^2 - \lambda v^2H^2 - \lambda vH^3 - \frac{1}{4}\lambda H^4 \\
&= \frac{1}{8}m_H^2v^2 - \frac{1}{2}m_H^2H^2 - \frac{1}{2}\frac{m_H^2}{v}H^3 - \frac{1}{8}\frac{m_H^2}{v^2}H^4, \tag{75}
\end{aligned}$$

其中 Higgs 玻色子的质量为

$$m_H \equiv \sqrt{2}\mu, \quad m_H^2 = 2\mu^2 = 2\lambda v^2. \tag{76}$$

利用

$$\begin{aligned}
g'B_\mu + gW_\mu^3 &= g'(c_\mathrm{W}A_\mu - s_\mathrm{W}Z_\mu) + g(s_\mathrm{W}A_\mu + c_\mathrm{W}Z_\mu) = 2eA_\mu + \frac{g^2-g'^2}{\sqrt{g^2+g'^2}}Z_\mu \\
&= 2eA_\mu + \frac{g}{c_\mathrm{W}}(c_\mathrm{W}^2-s_\mathrm{W}^2)Z_\mu, \tag{77}
\end{aligned}$$

有

$$\begin{aligned}
g'B_\mu Y_H + gW_\mu^a\tau^a &= \frac{1}{2}\begin{pmatrix} g'B_\mu + gW_\mu^3 & g(W_\mu^1-iW_\mu^2) \\ g(W_\mu^1+iW_\mu^2) & g'B_\mu - gW_\mu^3 \end{pmatrix} \\
&= \begin{pmatrix} eA_\mu + \frac{g}{2c_\mathrm{W}}(c_\mathrm{W}^2-s_\mathrm{W}^2)Z_\mu & \frac{1}{\sqrt{2}}gW_\mu^+ \\ \frac{1}{\sqrt{2}}gW_\mu^- & -\frac{g}{2c_\mathrm{W}}Z_\mu \end{pmatrix}. \tag{78}
\end{aligned}$$

于是，在幺正规范下，

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

$$
\begin{aligned}
&= \left| \begin{pmatrix} \partial_\mu - ieA_\mu - \dfrac{ig}{2c_{\mathrm W}}(c_{\mathrm W}^2 - s_{\mathrm W}^2)Z_\mu & -\dfrac{i}{\sqrt{2}}gW_\mu^+ \\[2mm] -\dfrac{i}{\sqrt{2}}gW_\mu^- & \partial_\mu + \dfrac{ig}{2c_{\mathrm W}}Z_\mu \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix} \right|^2 \\[3mm]
&= \frac{1}{2}\left(\frac{i}{\sqrt{2}}gW_\mu^-(v+H),\ \partial_\mu H - \frac{ig}{2c_{\mathrm W}}Z_\mu(v+H) \right) \begin{pmatrix} -\dfrac{i}{\sqrt{2}}gW_\mu^+(v+H) \\[2mm] \partial_\mu H + \dfrac{ig}{2c_{\mathrm W}}Z_\mu(v+H) \end{pmatrix} \\[3mm]
&= \frac{1}{2}(\partial^\mu H)(\partial_\mu H) + (v+H)^2\left(\frac{g^2}{4}W_\mu^+ W^{-\mu} + \frac{g^2}{8c_{\mathrm W}^2}Z_\mu Z^\mu \right) \\[3mm]
&= \frac{1}{2}(\partial^\mu H)(\partial_\mu H) + m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu \\[3mm]
&\quad + gm_W H W_\mu^+ W^{-\mu} + \frac{gm_Z}{2c_{\mathrm W}}HZ_\mu Z^\mu + \frac{g^2}{4}H^2 W_\mu^+ W^{-\mu} + \frac{g^2}{8c_{\mathrm W}^2}H^2 Z_\mu Z^\mu.
\end{aligned}
\tag{79}
$$

故 $W^\pm$ 和 Z 玻色子获得质量，分别为

$$
m_{\mathrm W} \equiv \frac{gv}{2}, \quad m_Z \equiv \frac{gv}{2c_{\mathrm W}} = \frac{m_{\mathrm W}}{c_{\mathrm W}} = \frac{v}{2}\sqrt{g^2 + g'^2}.
\tag{80}
$$

$Y = -1/2$ 的 Higgs 场共轭态为

$$
\tilde\Phi(x) = i\sigma^2 \Phi^*(x) = \begin{pmatrix} & 1 \\ -1 & \end{pmatrix} \begin{pmatrix} \phi^-(x) \\ \phi^{0*}(x) \end{pmatrix} = \begin{pmatrix} \phi^{0*}(x) \\ -\phi^-(x) \end{pmatrix},
\tag{81}
$$

其中 $\phi^- \equiv (\phi^+)^*$。在幺正规范下，$\tilde\Phi(x)$ 化为

$$
\tilde\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} & 1 \\ -1 & \end{pmatrix} \begin{pmatrix} 0 \\ v+H(x) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} v+H(x) \\ 0 \end{pmatrix}.
\tag{82}
$$

Yukawa 耦合项是

$$
\begin{aligned}
\mathcal{L}_{\mathrm Y} &= -\tilde y_d^{ij} \bar Q_{i\mathrm L} d_{j\mathrm R}' \Phi - y_{u_i} \bar Q_{i\mathrm L} u_{i\mathrm R} \tilde\Phi - y_{\ell_i} \bar L_{i\mathrm L} \ell_{i\mathrm R} \Phi + h.c. \\[2mm]
&= -\frac{1}{\sqrt{2}}(v+H)\bar d_{l\mathrm L} V_{li}^\dagger \tilde y_d^{ij} V_{jk} d_{k\mathrm R} - \frac{y_{u_i}}{\sqrt{2}}(v+H)\bar u_{i\mathrm L} u_{i\mathrm R} - \frac{y_{\ell_i}}{\sqrt{2}}(v+H)\bar\ell_{i\mathrm L}\ell_{i\mathrm R} + h.c. \\[2mm]
&= -m_{d_i}\bar d_i d_i - m_{u_i}\bar u_i u_i - m_{\ell_i}\bar\ell_i \ell_i - \frac{m_{d_i}}{v}H\bar d_i d_i - \frac{m_{u_i}}{v}H\bar u_i u_i - \frac{m_{\ell_i}}{v}H\bar\ell_i \ell_i.
\end{aligned}
\tag{83}
$$

这里 CKM 矩阵将 $\tilde y_d^{ij}$ 对角化：

$$
V_{li}^\dagger \tilde y_d^{ij} V_{jk} = y_{d_k}\delta_{lk}.
\tag{84}
$$

通过 Yukawa 耦合，费米子获得了质量，

$$
m_{d_i} \equiv \frac{1}{\sqrt{2}}y_{d_i}v, \quad m_{u_i} \equiv \frac{1}{\sqrt{2}}y_{u_i}v, \quad m_{\ell_i} \equiv \frac{1}{\sqrt{2}}y_{\ell_i}v.
\tag{85}
$$
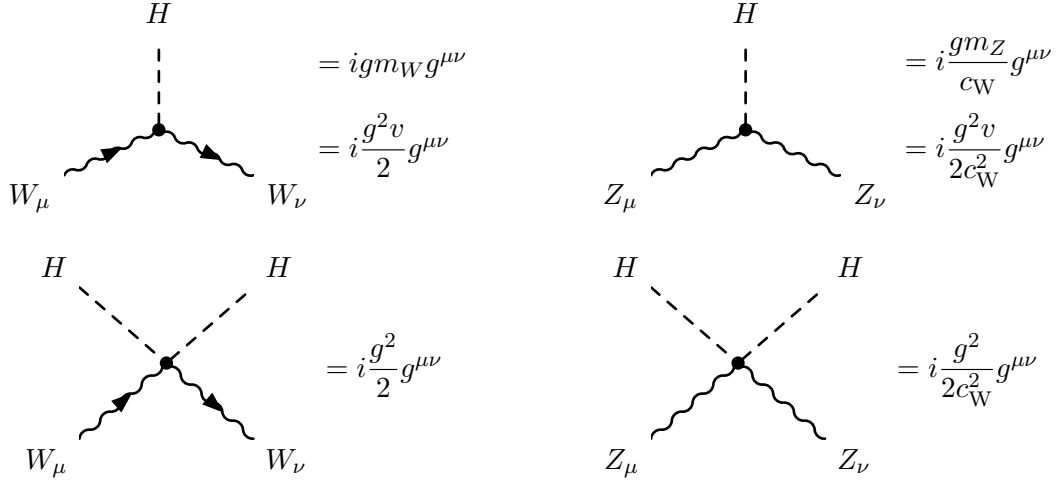
下面给出幺正规范下的顶点费曼规则。

Higgs 玻色子自耦合:
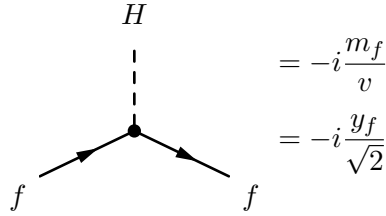
$$= -3i\frac{m_H^2}{v}$$
$$= -6i\lambda v$$

$$= -3i\frac{m_H^2}{v^2}$$
$$= -6i\lambda$$

Higgs 玻色子与电弱规范玻色子的耦合:

$$= igm_W g^{\mu\nu}$$
$$= i\frac{g^2 v}{2}g^{\mu\nu}$$

$$= i\frac{gm_Z}{c_W}g^{\mu\nu}$$
$$= i\frac{g^2 v}{2c_W^2}g^{\mu\nu}$$

$$= i\frac{g^2}{2}g^{\mu\nu}$$

$$= i\frac{g^2}{2c_W^2}g^{\mu\nu}$$

Higgs 玻色子与费米子的耦合:

$$= -i\frac{m_f}{v}$$
$$= -i\frac{y_f}{\sqrt{2}}$$

7 R_ξ 规范相关拉氏量和费曼规则

将 Higgs 场参数化为

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \frac{1}{\sqrt{2}}[v + H(x) + i\chi(x)] \end{pmatrix}, \tag{86}$$

其中 ϕ^+ 和 χ 是 Nambu-Goldstone 标量场。那么, $\tilde{\Phi}(x)$ 的形式是

$$\tilde{\Phi}(x) = \begin{pmatrix} \phi^{0*}(x) \\ -\phi^-(x) \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}[v + H(x) - i\chi(x)] \\ -\phi^-(x) \end{pmatrix}. \tag{87}$$

由

$$\Phi^\dagger \Phi = \frac{1}{2}(v^2 + H^2 + 2vH + \chi^2) + |\phi^+|^2,$$

16

$$(\Phi^\dagger\Phi)^2 = \frac{1}{4}(v^2 + H^2 + 2vH + \chi^2)^2 + |\phi^+|^4 + |\phi^+|^2(v^2 + H^2 + 2vH + \chi^2), \tag{88}$$

可得 Higgs 场势能项

$$\begin{aligned}
-V_{\mathrm{H}}(\Phi) &= \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 \\
&= \frac{1}{2}\mu^2(v^2 + H^2 + 2vH + \chi^2) + \mu^2|\phi^+|^2 - \frac{1}{4}\lambda(v^2 + H^2 + 2vH + \chi^2)^2 - \lambda|\phi^+|^4 \\
&\quad - \lambda|\phi^+|^2(v^2 + H^2 + 2vH + \chi^2) \\
&= \frac{1}{2}\left(\mu^2 - \frac{1}{2}\lambda v^2\right)v^2 + \frac{1}{2}(\mu^2 - 3\lambda v^2)H^2 + (\mu^2 - \lambda v^2)vH + \frac{1}{2}(\mu^2 - \lambda v^2)\chi^2 - \frac{1}{4}\lambda H^4 - \frac{1}{4}\lambda\chi^4 - \lambda vH^3 \\
&\quad - \frac{1}{2}\lambda H^2\chi^2 - \lambda vH\chi^2 + (\mu^2 - \lambda v^2)|\phi^+|^2 - \lambda|\phi^+|^4 - \lambda|\phi^+|^2(H^2 + 2vH + \chi^2) \\
&= \frac{1}{4}\lambda v^4 - \lambda v^2 H^2 - \frac{1}{4}\lambda H^4 - \frac{1}{4}\lambda\chi^4 - \lambda vH^3 - \frac{1}{2}\lambda H^2\chi^2 - \lambda vH\chi^2 - \lambda\phi^+\phi^-(\phi^+\phi^- + H^2 + 2vH + \chi^2) \\
&= \frac{1}{8}m_H^2 v^2 - \frac{1}{2}m_H^2 H^2 - \frac{m_H^2}{2v}H^3 - \frac{m_H^2}{8v^2}H^4 - \frac{m_H^2}{2v}H\chi^2 - \frac{m_H^2}{4v^2}H^2\chi^2 - \frac{m_H^2}{8v^2}\chi^4 \\
&\quad - \frac{m_H^2}{2v^2}\phi^+\phi^-(\phi^+\phi^- + H^2 + 2vH + \chi^2). \tag{89}
\end{aligned}$$

由于

$$V_{li}^\dagger\tilde{y}_d^{ij}V_{jk} = y_{d_k}\delta_{lk}, \quad \tilde{y}_d^{ij} = V_{ik}y_{d_k}V_{kj}^\dagger, \tag{90}$$

有

$$\begin{aligned}
-\tilde{y}_d^{ij}\bar{Q}_{i\mathrm{L}}d'_{j\mathrm{R}}\Phi &= -\tilde{y}_d^{ij}\left[\bar{u}_{i\mathrm{L}}d'_{j\mathrm{R}}\phi^+ + \frac{1}{\sqrt{2}}\bar{d}'_{i\mathrm{L}}d'_{j\mathrm{R}}(v + H + i\chi)\right] \\
&= -\left[\bar{u}_{i\mathrm{L}}V_{ik}y_{d_k}V_{kj}^\dagger V_{jl}d_{l\mathrm{R}}\phi^+ + \frac{1}{\sqrt{2}}\bar{d}_{l\mathrm{L}}V_{li}^\dagger\tilde{y}_d^{ij}V_{jk}d_{k\mathrm{R}}(v + H + i\chi)\right] \\
&= -\left[y_{d_j}\bar{u}_{i\mathrm{L}}V_{ij}d_{j\mathrm{R}}\phi^+ + \frac{1}{\sqrt{2}}y_{d_i}\bar{d}_{i\mathrm{L}}d_{i\mathrm{R}}(v + H + i\chi)\right], \tag{91}
\end{aligned}$$

则 Yukawa 耦合项为

$$\begin{aligned}
\mathcal{L}_{\mathrm{Y}} &= -\tilde{y}_d^{ij}\bar{Q}_{i\mathrm{L}}d'_{j\mathrm{R}}\Phi - y_{u_i}\bar{Q}_{i\mathrm{L}}u_{i\mathrm{R}}\tilde{\Phi} - y_{\ell_i}\bar{L}_{i\mathrm{L}}\ell_{i\mathrm{R}}\Phi + \mathrm{h.c.} \\
&= -\left[y_{d_j}\bar{u}_{i\mathrm{L}}V_{ij}d_{j\mathrm{R}}\phi^+ + \frac{1}{\sqrt{2}}y_{d_i}\bar{d}_{i\mathrm{L}}d_{i\mathrm{R}}(v + H + i\chi)\right] - y_{u_i}\left[\frac{1}{\sqrt{2}}\bar{u}_{i\mathrm{L}}u_{i\mathrm{R}}(v + H - i\chi) - \bar{d}_{j\mathrm{L}}V_{ji}^\dagger u_{i\mathrm{R}}\phi^-\right] \\
&\quad - y_{\ell_i}\left[\bar{\nu}_{i\mathrm{L}}\ell_{i\mathrm{R}}\phi^+ + \frac{1}{\sqrt{2}}\bar{\ell}_{i\mathrm{L}}\ell_{i\mathrm{R}}(v + H + i\chi)\right] + \mathrm{h.c.} \\
&= -m_{d_i}\bar{d}_{i\mathrm{L}}d_{i\mathrm{R}} - m_{u_i}\bar{u}_{i\mathrm{L}}u_{i\mathrm{R}} - m_{\ell_i}\bar{\ell}_{i\mathrm{L}}\ell_{i\mathrm{R}} - \frac{m_{d_i}}{v}\bar{d}_{i\mathrm{L}}d_{i\mathrm{R}}(H + i\chi) - \frac{m_{u_i}}{v}\bar{u}_{i\mathrm{L}}u_{i\mathrm{R}}(H - i\chi) \\
&\quad - \frac{m_{\ell_i}}{v}\bar{\ell}_{i\mathrm{L}}\ell_{i\mathrm{R}}(H + i\chi) - \frac{\sqrt{2}m_{d_j}}{v}\bar{u}_{i\mathrm{L}}V_{ij}d_{j\mathrm{R}}\phi^+ + \frac{\sqrt{2}m_{u_i}}{v}\bar{d}_{j\mathrm{L}}V_{ji}^\dagger u_{i\mathrm{R}}\phi^- - \frac{\sqrt{2}m_{\ell_i}}{v}\bar{\nu}_{i\mathrm{L}}\ell_{i\mathrm{R}}\phi^+ + \mathrm{h.c.} \\
&= -m_{d_i}\bar{d}_i d_i - m_{u_i}\bar{u}_i u_i - m_{\ell_i}\bar{\ell}_i\ell_i - \frac{m_{d_i}}{v}H\bar{d}_i d_i - \frac{m_{u_i}}{v}H\bar{u}_i u_i - \frac{m_{\ell_i}}{v}H\bar{\ell}_i\ell_i \\
&\quad - \frac{m_{d_i}}{v}\chi\bar{d}_i i\gamma_5 d_i + \frac{m_{u_i}}{v}\chi\bar{u}_i i\gamma_5 u_i - \frac{m_{\ell_i}}{v}\chi\bar{\ell}_i i\gamma_5\ell_i + \frac{\sqrt{2}V_{ij}}{v}\phi^+\bar{u}_i(m_{u_i}P_{\mathrm{L}} - m_{d_j}P_{\mathrm{R}})d_j \\
&\quad - \frac{\sqrt{2}V_{ji}^\dagger}{v}\phi^-\bar{d}_j(m_{d_j}P_{\mathrm{L}} - m_{u_i}P_{\mathrm{R}})u_i - \frac{\sqrt{2}m_{\ell_i}}{v}(\phi^+\bar{\nu}_i P_{\mathrm{R}}\ell_i + \phi^-\bar{\ell}_i P_{\mathrm{L}}\nu_i). \tag{92}
\end{aligned}$$

利用

$$D_\mu \Phi = \begin{pmatrix} \partial_\mu - ieA_\mu - \dfrac{ig}{2c_{\mathrm{W}}}(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)Z_\mu & -\dfrac{i}{\sqrt{2}}gW_\mu^+ \\[2mm] -\dfrac{i}{\sqrt{2}}gW_\mu^- & \partial_\mu + \dfrac{ig}{2c_{\mathrm{W}}}Z_\mu \end{pmatrix} \begin{pmatrix} \phi^+ \\[2mm] \dfrac{1}{\sqrt{2}}(v + H + i\chi) \end{pmatrix}$$

$$= \begin{pmatrix} \partial_\mu\phi^+ - i\left[eA_\mu + \dfrac{g(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)}{2c_{\mathrm{W}}}Z_\mu\right]\phi^+ - \dfrac{ig}{2}W_\mu^+(H + i\chi) - im_W W_\mu^+ \\[3mm] \dfrac{1}{\sqrt{2}}\left[\partial_\mu(H + i\chi) - igW_\mu^-\phi^+ + \dfrac{ig}{2c_{\mathrm{W}}}Z_\mu(H + i\chi) + im_Z Z_\mu\right] \end{pmatrix}, \tag{93}$$

可将 Higgs 场协变动能项化为

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

$$= \left|\partial_\mu\phi^+ - i\left[eA_\mu + \frac{g(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)}{2c_{\mathrm{W}}}Z_\mu\right]\phi^+ - \frac{ig}{2}W_\mu^+(H + i\chi) - im_W W_\mu^+\right|^2$$

$$+ \frac{1}{2}\left|\partial_\mu(H + i\chi) - igW_\mu^-\phi^+ + \frac{ig}{2c_{\mathrm{W}}}Z_\mu(H + i\chi) + im_Z Z_\mu\right|^2$$

$$= (\partial^\mu\phi^+)(\partial_\mu\phi^-) + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) + \frac{1}{2}(\partial^\mu\chi)(\partial_\mu\chi)$$

$$+ \left(-i\partial^\mu\phi^- \left\{\left[eA_\mu + \frac{g(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)}{2c_{\mathrm{W}}}Z_\mu\right]\phi^+ + \frac{g}{2}W_\mu^+(H + i\chi) + m_W W_\mu^+\right\} + \text{h.c.}\right)$$

$$+ \left\{-\frac{i}{2}\partial^\mu(H - i\chi)\left[gW_\mu^-\phi^+ - \frac{g}{2c_{\mathrm{W}}}Z_\mu(H + i\chi) - m_Z Z_\mu\right] + \text{h.c.}\right\}$$

$$+ \left|\left[eA_\mu + \frac{g(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)}{2c_{\mathrm{W}}}Z_\mu\right]\phi^+ + \frac{g}{2}W_\mu^+(H + i\chi) + m_W W_\mu^+\right|^2$$

$$+ \frac{1}{2}\left|gW_\mu^-\phi^+ - \frac{g}{2c_{\mathrm{W}}}Z_\mu(H + i\chi) - m_Z Z_\mu\right|^2$$

$$= (\partial^\mu\phi^+)(\partial_\mu\phi^-) + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) + \frac{1}{2}(\partial^\mu\chi)(\partial_\mu\chi)$$

$$+ m_W^2 W^{-\mu}W_\mu^+ + \frac{1}{2}m_Z^2 Z^\mu Z_\mu + gm_W H W_\mu^+ W^{-\mu} + \frac{gm_Z}{2c_{\mathrm{W}}}H Z^\mu Z_\mu$$

$$+ \frac{g}{2}[W_\mu^+\phi^- i\overleftrightarrow{\partial^\mu}(H + i\chi) + \text{h.c.}] + eA_\mu\phi^- i\overleftrightarrow{\partial^\mu}\phi^+ + \frac{g}{2c_{\mathrm{W}}}Z_\mu[i\chi i\overleftrightarrow{\partial^\mu}H + (c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)\phi^- i\overleftrightarrow{\partial^\mu}\phi^+]$$

$$+ \frac{g^2}{4}W_\mu^+ W^{-\mu}(2\phi^+\phi^- + H^2 + \chi^2) + e^2 A_\mu A^\mu\phi^+\phi^- + \frac{g^2}{4c_{\mathrm{W}}^2}Z_\mu Z^\mu\left[(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)^2\phi^+\phi^- + \frac{1}{2}H^2 + \frac{1}{2}\chi^2\right]$$

$$+ \left[\frac{eg}{2}W_\mu^+ A^\mu\phi^-(H + i\chi) - \frac{g^2 s_{\mathrm{W}}^2}{2c_{\mathrm{W}}}W_\mu^+ Z^\mu\phi^-(H + i\chi) + \text{h.c.}\right] + \frac{eg}{c_{\mathrm{W}}}(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)A_\mu Z^\mu\phi^+\phi^-$$

$$+ (em_W A^\mu\phi^+ W_\mu^- - gs_{\mathrm{W}}^2 m_Z Z^\mu\phi^+ W_\mu^- + \text{h.c.}) + \mathcal{L}_{\mathrm{b1}}, \tag{94}$$

其中

$$\mathcal{L}_{\mathrm{b1}} = -im_W(\partial^\mu\phi^-)W_\mu^+ + im_W(\partial^\mu\phi^+)W_\mu^- + m_Z(\partial^\mu\chi)Z_\mu. \tag{95}$$

R_ξ 规范的规范固定函数设为

$$G^\pm = \frac{1}{\sqrt{\xi_W}}(\partial^\mu W_\mu^\pm \mp i\xi_W m_W\phi^\pm), \quad G^Z = \frac{1}{\sqrt{\xi_Z}}(\partial^\mu Z_\mu - \xi_Z m_Z\chi), \quad G^\gamma = \frac{1}{\sqrt{\xi_\gamma}}\partial^\mu A_\mu, \tag{96}$$

18

它们在路径积分量子化中的泛函积分形式为

$$\int \mathcal{D}\omega^+ \int \mathcal{D}\omega^- \int \mathcal{D}\omega^Z \int \mathcal{D}\omega^\gamma \exp\left[-i\int d^4x \left(\omega^+\omega^- + \frac{1}{2}\omega^Z\omega^Z + \frac{1}{2}\omega^\gamma\omega^\gamma\right)\right]$$
$$\times \delta(G^+ - \omega^+)\delta(G^- - \omega^-)\delta(G^Z - \omega^Z)\delta(G^\gamma - \omega^\gamma)$$
$$= \exp\left[-i\int d^4x \left(G^+G^- + \frac{1}{2}G^ZG^Z + \frac{1}{2}G^\gamma G^\gamma\right)\right]. \tag{97}$$

由此可得拉氏量中的规范固定项

$$\begin{aligned}
\mathcal{L}_{\text{EW,GF}} &= -G^+G^- - \frac{1}{2}(G^Z)^2 - \frac{1}{2}(G^\gamma)^2 \\
&= -\frac{1}{\xi_W}(\partial^\mu W_\mu^+ - i\xi_W m_W \phi^+)(\partial^\nu W_\nu^- + i\xi_W m_W \phi^-) - \frac{1}{2\xi_Z}(\partial^\mu Z_\mu - \xi_Z m_Z \chi)^2 - \frac{1}{2\xi_\gamma}(\partial^\mu A_\mu)^2 \\
&= -\frac{1}{\xi_W}(\partial^\mu W_\mu^+)(\partial^\nu W_\nu^-) - \frac{1}{2\xi_Z}(\partial^\mu Z_\mu)^2 - \frac{1}{2\xi_\gamma}(\partial^\mu A_\mu)^2 - \xi_W m_W^2 \phi^+\phi^- - \frac{1}{2}\xi_Z m_Z^2 \chi^2 + \mathcal{L}_{\text{b2}}. \tag{98}
\end{aligned}$$

可见，Nambu-Goldstein 玻色子在 R_ξ 规范下具有依赖于 ξ_W 和 ξ_Z 的非物理质量，

$$m_\phi = \sqrt{\xi_W}\, m_W, \quad m_\chi = \sqrt{\xi_Z}\, m_Z. \tag{99}$$

这里，

$$\mathcal{L}_{\text{b2}} = -im_W \phi^-(\partial^\mu W_\mu^+) + im_W \phi^+ \partial^\mu W_\mu^- + m_Z \chi \partial^\mu Z_\mu. \tag{100}$$

由于

$$\mathcal{L}_{\text{b1}} + \mathcal{L}_{\text{b2}} = -im_W \partial^\mu(\phi^- W_\mu^+) + im_W \partial^\mu(\phi^+ W_\mu^-) + m_Z \partial^\mu(\chi Z_\mu), \tag{101}$$

这两项体现为全散度，不会有物理效应。可见，协变动能项中规范场与 Nambu-Goldstein 标量场之间的双线性耦合项 $\mathcal{L}_{\text{b1}}$ 被规范固定项中的 $\mathcal{L}_{\text{b2}}$ 抵消掉，这就是如此选取规范固定函数的目的。

这样一来，电弱规范场传播子相关拉氏量变成

$$\begin{aligned}
\mathcal{L}_{\text{EW,prop}} &= (\partial_\mu W_\nu^+)(\partial^\nu W^{-\mu}) - (\partial_\mu W_\nu^+)(\partial^\mu W^{-\nu}) - \frac{1}{\xi_W}(\partial^\mu W_\mu^+)(\partial^\nu W_\nu^-) + m_W^2 W^{-\mu}W_\mu^+ \\
&\quad + \frac{1}{2}\left[(\partial_\mu Z_\nu)(\partial^\nu Z^\mu) - (\partial_\mu Z_\nu)(\partial^\mu Z^\nu) - \frac{1}{\xi_Z}(\partial^\mu Z_\mu)^2 + m_Z^2 Z^\mu Z_\mu\right] \\
&\quad + \frac{1}{2}\left[(\partial_\mu A_\nu)(\partial^\nu A^\mu) - (\partial_\mu A_\nu)(\partial^\mu A^\nu) - \frac{1}{\xi_\gamma}(\partial^\mu A_\mu)^2\right] \\
&\to W_\mu^+\left[g^{\mu\nu}(\partial^2 + m_W^2) - \left(1 - \frac{1}{\xi_W}\right)\partial^\mu\partial^\nu\right]W_\nu^- + \frac{1}{2}Z_\mu\left[g^{\mu\nu}(\partial^2 + m_Z^2) - \left(1 - \frac{1}{\xi_Z}\right)\partial^\mu\partial^\nu\right]Z_\nu \\
&\quad + \frac{1}{2}A_\mu\left[g^{\mu\nu}\partial^2 - \left(1 - \frac{1}{\xi_\gamma}\right)\partial^\mu\partial^\nu\right]A_\nu. \tag{102}
\end{aligned}$$

于是，光子的传播子与胶子形式类似，为

$$\frac{-i}{p^2 + i\varepsilon}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}(1 - \xi_\gamma)\right]. \tag{103}$$

将 $W^\pm$ 传播子相关拉氏量变换到动量空间，得

$$- g^{\mu\nu}(p^2 - m_W^2) + \left(1 - \frac{1}{\xi_W}\right) p^\mu p^\nu = -\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right)(p^2 - m_W^2) - \frac{p^\mu p^\nu}{p^2}\frac{p^2 - \xi_W m_W^2}{\xi_W}, \quad (104)$$

它的逆矩阵是

$$- \frac{1}{p^2 - m_W^2}\left(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) - \frac{\xi_W}{p^2 - \xi_W m_W^2}\frac{p_\mu p_\nu}{p^2} = -\frac{1}{p^2 - m_W^2}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2 - \xi_W m_W^2}(1 - \xi_W)\right], \quad (105)$$

这是因为由

$$\left(g_{\rho\mu} - \frac{p_\rho p_\mu}{p^2}\right)\frac{p^\mu p^\nu}{p^2} = \frac{p_\rho p^\nu}{p^2} - \frac{p_\rho p^\nu}{p^2} = 0, \quad \left(g_{\rho\mu} - \frac{p_\rho p_\mu}{p^2}\right)\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right) = \delta_\rho^\nu - \frac{p_\rho p^\nu}{p^2} \quad (106)$$

可得

$$\left[-\frac{1}{p^2 - m_W^2}\left(g_{\rho\mu} - \frac{p_\rho p_\mu}{p^2}\right) - \frac{\xi_W}{p^2 - \xi_W m_W^2}\frac{p_\rho p_\mu}{p^2}\right]\left[-\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right)(p^2 - m_W^2) - \frac{p^\mu p^\nu}{p^2}\frac{p^2 - \xi_W m_W^2}{\xi_W}\right]$$

$$= \delta_\rho^\nu - \frac{p_\rho p^\nu}{p^2} + \frac{p_\rho p^\nu}{p^2} = \delta_\rho^\nu. \quad (107)$$

从而，$W^\pm$ 传播子的形式为

$$\frac{-i}{p^2 - m_W^2 + i\varepsilon}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2 - \xi_W m_W^2}(1 - \xi_W)\right]. \quad (108)$$

同理，Z 传播子的形式为

$$\frac{-i}{p^2 - m_Z^2 + i\varepsilon}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2 - \xi_Z m_Z^2}(1 - \xi_Z)\right]. \quad (109)$$

电弱规范场的无穷小规范变换形式是

$$\delta W_\mu^a = \frac{1}{g}\partial_\mu \alpha^a + \varepsilon^{abc} W_\mu^b \alpha^c, \quad \delta B_\mu = \frac{1}{g'}\partial_\mu \alpha^Y. \quad (110)$$

定义

$$\alpha^\pm \equiv \frac{1}{\sqrt{2}}(\alpha^1 \mp i\alpha^2), \quad \alpha^Z \equiv \alpha^3 - \alpha^Y, \quad \alpha^\gamma \equiv s_W^2 \alpha^3 + c_W^2 \alpha^Y, \quad (111)$$

利用

$$\varepsilon^{1bc} W_\mu^b \alpha^c = W_\mu^2 \alpha^3 - W_\mu^3 \alpha^2, \quad \varepsilon^{2bc} W_\mu^b \alpha^c = -W_\mu^1 \alpha^3 + W_\mu^3 \alpha^1, \quad (112)$$

$$\pm i\sqrt{2}\alpha^\pm = \pm i\alpha^1 + \alpha^2, \quad \pm i\sqrt{2}W_\mu^\pm = \pm iW_\mu^1 + W_\mu^2, \quad (113)$$

有

$$\varepsilon^{1bc} W_\mu^b \alpha^c \mp i\varepsilon^{2bc} W_\mu^b \alpha^c = (W_\mu^2 \alpha^3 - W_\mu^3 \alpha^2) \mp i(-W_\mu^1 \alpha^3 + W_\mu^3 \alpha^1) = (W_\mu^2 \pm iW_\mu^1)\alpha^3 - W_\mu^3(\alpha^2 \pm i\alpha^1)$$

$$= \pm i\sqrt{2}W_\mu^\pm(c_W^2 \alpha^Z + \alpha^\gamma) \mp i\sqrt{2}(s_W A_\mu + c_W Z_\mu)\alpha^\pm, \quad (114)$$

$$\varepsilon^{3bc} W_\mu^b \alpha^c = W_\mu^1 \alpha^2 - W_\mu^2 \alpha^1 = \frac{1}{\sqrt{2}}(W_\mu^+ + W_\mu^-)\frac{i}{\sqrt{2}}(\alpha^+ - \alpha^-) - \frac{i}{\sqrt{2}}(W_\mu^+ - W_\mu^-)\frac{1}{\sqrt{2}}(\alpha^+ + \alpha^-)$$

$$= -i(W_\mu^+ \alpha^- - W_\mu^- \alpha^+). \quad (115)$$

因此，

$$\delta W_\mu^+ = \frac{1}{\sqrt{2}}(\delta W_\mu^1 - i\delta W_\mu^2) = \frac{1}{\sqrt{2}g}\partial_\mu(\alpha^1 - i\alpha^2) + \frac{1}{\sqrt{2}}(\varepsilon^{1bc}W_\mu^b\alpha^c - i\varepsilon^{2bc}W_\mu^b\alpha^c)$$

$$= \frac{1}{g}\partial_\mu\alpha^+ - i(s_W A_\mu + c_W Z_\mu)\alpha^+ + iW_\mu^+(c_W^2\alpha^Z + \alpha^\gamma), \tag{116}$$

$$\delta W_\mu^- = (\delta W_\mu^+)^\dagger = \frac{1}{g}\partial_\mu\alpha^- + i(s_W A_\mu + c_W Z_\mu)\alpha^- - iW_\mu^-(c_W^2\alpha^Z + \alpha^\gamma), \tag{117}$$

$$\delta Z_\mu^a = c_W\delta W_\mu^3 - s_W\delta B_\mu = \frac{c_W}{g}\partial_\mu\alpha^3 + c_W\varepsilon^{3bc}W_\mu^b\alpha^c - \frac{s_W}{g'}\partial_\mu\alpha^Y = \frac{c_W}{g}\partial_\mu\alpha^Z - ic_W(W_\mu^+\alpha^- - W_\mu^-\alpha^+), \tag{118}$$

$$\delta A_\mu = s_W\delta W_\mu^3 + c_W\delta B_\mu = \frac{s_W}{g}\partial_\mu\alpha^3 + s_W\varepsilon^{3bc}W_\mu^b\alpha^c + \frac{c_W}{g'}\partial_\mu\alpha^Y = \frac{1}{e}\partial_\mu\alpha^\gamma - is_W(W_\mu^+\alpha^- - W_\mu^-\alpha^+). \tag{119}$$

另一方面，根据

$$\alpha^a T^a + \alpha^Y Y_H = \frac{1}{2}(\alpha^a\sigma^a + \alpha^Y) = \frac{1}{2}\begin{pmatrix} \alpha^3 + \alpha^Y & \alpha^1 - i\alpha^2 \\ \alpha^1 + i\alpha^2 & -\alpha^3 + \alpha^Y \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 2\alpha^\gamma + (c_W^2 - s_W^2)\alpha^Z & \sqrt{2}\alpha^+ \\ \sqrt{2}\alpha^- & -\alpha^Z \end{pmatrix}, \tag{120}$$

可知 Higgs 场的无穷小规范变换形式为

$$\delta\Phi = i(\alpha^a T^a + \alpha^Y Y_H)\Phi = \frac{i}{2}\begin{pmatrix} 2\alpha^\gamma + (c_W^2 - s_W^2)\alpha^Z & \sqrt{2}\alpha^+ \\ \sqrt{2}\alpha^- & -\alpha^Z \end{pmatrix}\begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + H + i\chi) \end{pmatrix}$$

$$= \begin{pmatrix} \frac{i}{2}[\phi^+[2\alpha^\gamma + (c_W^2 - s_W^2)\alpha^Z] + (v + H + i\chi)\alpha^+] \\ \frac{1}{\sqrt{2}}\left[i\phi^+\alpha^- - \frac{1}{2}(iv + iH - \chi)\alpha^Z\right] \end{pmatrix} = \begin{pmatrix} \delta\phi^+ \\ \frac{1}{\sqrt{2}}(\delta H + i\delta\chi) \end{pmatrix}. \tag{121}$$

利用

$$\text{Re}(\phi^+\alpha^-) = \frac{1}{2}(\phi^+\alpha^- + \phi^-\alpha^+), \quad \text{Im}(\phi^+\alpha^-) = -\frac{i}{2}(\phi^+\alpha^- - \phi^-\alpha^+), \tag{122}$$

可得

$$\delta\phi^+ = \frac{i}{2}\{\phi^+[2\alpha^\gamma + (c_W^2 - s_W^2)\alpha^Z] + (v + H + i\chi)\alpha^+\}, \tag{123}$$

$$\delta\phi^- = -\frac{i}{2}\{\phi^-[2\alpha^\gamma + (c_W^2 - s_W^2)\alpha^Z] + (v + H - i\chi)\alpha^-\}, \tag{124}$$

$$\delta H = \frac{1}{2}[i(\phi^+\alpha^- - \phi^-\alpha^+) + \chi\alpha^Z], \quad \delta\chi = \frac{1}{2}[\phi^+\alpha^- + \phi^-\alpha^+ - (v + H)\alpha^Z]. \tag{125}$$

于是，规范固定函数的无穷小规范变换为

$$\sqrt{\xi_W}\,\delta G^+ = \partial^\mu\delta W_\mu^+ - i\xi_W m_W\delta\phi^+$$

$$= \partial^\mu\left[\frac{1}{g}\partial_\mu\alpha^+ - i(s_W A_\mu + c_W Z_\mu)\alpha^+ + iW_\mu^+(c_W^2\alpha^Z + \alpha^\gamma)\right]$$

$$+ \frac{1}{2}\xi_W m_W\left\{\phi^+[2\alpha^\gamma + (c_W^2 - s_W^2)\alpha^Z] + (v + H + i\chi)\alpha^+\right\}, \tag{126}$$

$$\sqrt{\xi_W}\,\delta G^- = \partial^\mu\delta W_\mu^- + i\xi_W m_W\delta\phi^-$$

$$= \partial^\mu\left[\frac{1}{g}\partial_\mu\alpha^- + i(s_W A_\mu + c_W Z_\mu)\alpha^- - iW_\mu^-(c_W^2\alpha^Z + \alpha^\gamma)\right]$$

$$+ \frac{1}{2}\xi_W m_W \left\{ \phi^-[2\alpha^\gamma + (c_W^2 - s_W^2)\alpha^Z] + (v + H - i\chi)\alpha^- \right\}, \tag{127}$$

$$\sqrt{\xi_Z}\,\delta G^Z = \partial^\mu \delta Z_\mu - \xi_Z m_Z \delta\chi$$

$$= \partial^\mu \left[\frac{c_W}{g}\partial_\mu \alpha^Z - ic_W(W_\mu^+ \alpha^- - W_\mu^- \alpha^+) \right] - \frac{1}{2}\xi_Z m_Z \left[\phi^+ \alpha^- + \phi^- \alpha^+ - (v + H)\alpha^Z \right], \tag{128}$$

$$\sqrt{\xi_\gamma}\,\delta G^\gamma = \partial^\mu \delta A_\mu = \partial^\mu \left[\frac{1}{e}\partial_\mu \alpha^\gamma - is_W(W_\mu^+ \alpha^- - W_\mu^- \alpha^+) \right]. \tag{129}$$

因此,

$$\sqrt{\xi_W}\,g\frac{\delta G^+}{\delta\alpha^+} = \partial^2 + \xi_W m_W^2 - ie\partial^\mu A_\mu - igc_W\partial^\mu Z_\mu + \frac{1}{2}g\xi_W m_W(H + i\chi), \tag{130}$$

$$\frac{\sqrt{\xi_W}}{c_W}g\frac{\delta G^+}{\delta\alpha^Z} = igc_W\partial^\mu W_\mu^+ + \frac{g(c_W^2 - s_W^2)\xi_W m_W}{2c_W}\phi^+, \quad \sqrt{\xi_W}\,e\frac{\delta G^+}{\delta\alpha^\gamma} = ie\partial^\mu W_\mu^+ + e\xi_W m_W\phi^+, \tag{131}$$

$$\sqrt{\xi_W}\,g\frac{\delta G^-}{\delta\alpha^-} = \partial^2 + \xi_W m_W^2 + ie\partial^\mu A_\mu + igc_W\partial^\mu Z_\mu + \frac{1}{2}\xi_W g m_W(H - i\chi), \tag{132}$$

$$\frac{\sqrt{\xi_W}}{c_W}g\frac{\delta G^-}{\delta\alpha^Z} = -igc_W\partial^\mu W_\mu^- + \frac{g(c_W^2 - s_W^2)\xi_W m_W}{2c_W}\phi^-, \quad \sqrt{\xi_W}\,e\frac{\delta G^-}{\delta\alpha^\gamma} = -ie\partial^\mu W_\mu^- + e\xi_W m_W\phi^-, \tag{133}$$

$$\sqrt{\xi_Z}\,g\frac{\delta G^Z}{\delta\alpha^+} = igc_W\partial^\mu W_\mu^- - \frac{1}{2}g\xi_Z m_Z\phi^-, \quad \sqrt{\xi_Z}\,g\frac{\delta G^Z}{\delta\alpha^-} = -igc_W\partial^\mu W_\mu^+ - \frac{1}{2}g\xi_Z m_Z\phi^+, \tag{134}$$

$$\frac{\sqrt{\xi_Z}}{c_W}g\frac{\delta G^Z}{\delta\alpha^Z} = \partial^2 + \xi_Z m_Z^2 + \frac{g\xi_Z m_Z}{2c_W}H, \tag{135}$$

$$\sqrt{\xi_\gamma}\,g\frac{\delta G^\gamma}{\delta\alpha^+} = ie\partial^\mu W_\mu^-, \quad \sqrt{\xi_\gamma}\,g\frac{\delta G^\gamma}{\delta\alpha^-} = -ie\partial^\mu W_\mu^+, \quad \sqrt{\xi_\gamma}\,e\frac{\delta G^\gamma}{\delta\alpha^\gamma} = \partial^2. \tag{136}$$

最后, 得到以下 Faddeev-Popov 鬼场拉氏量,

$$\mathcal{L}_{\mathrm{EWG,FP}} = -\bar{\eta}^+ \left(\sqrt{\xi_W}\,g\frac{\delta G^+}{\delta\alpha^+} \right)\eta^+ - \bar{\eta}^Z \left(\sqrt{\xi_Z}\,g\frac{\delta G^Z}{\delta\alpha^+} \right)\eta^+ - \bar{\eta}^\gamma \left(\sqrt{\xi_\gamma}\,g\frac{\delta G^\gamma}{\delta\alpha^+} \right)\eta^+$$

$$-\bar{\eta}^- \left(\sqrt{\xi_W}\,g\frac{\delta G^-}{\delta\alpha^-} \right)\eta^- - \bar{\eta}^Z \left(\sqrt{\xi_Z}\,g\frac{\delta G^Z}{\delta\alpha^-} \right)\eta^- - \bar{\eta}^\gamma \left(\sqrt{\xi_\gamma}\,g\frac{\delta G^\gamma}{\delta\alpha^-} \right)\eta^-$$

$$-\bar{\eta}^Z \left(\frac{\sqrt{\xi_Z}}{c_W}g\frac{\delta G^Z}{\delta\alpha^Z} \right)\eta^Z - \bar{\eta}^+ \left(\frac{\sqrt{\xi_W}}{c_W}g\frac{\delta G^+}{\delta\alpha^Z} \right)\eta^Z - \bar{\eta}^- \left(\frac{\sqrt{\xi_W}}{c_W}g\frac{\delta G^-}{\delta\alpha^Z} \right)\eta^Z$$

$$-\bar{\eta}^\gamma \left(\sqrt{\xi_\gamma}\,e\frac{\delta G^\gamma}{\delta\alpha^\gamma} \right)\eta^\gamma - \bar{\eta}^+ \left(\sqrt{\xi_W}\,e\frac{\delta G^+}{\delta\alpha^\gamma} \right)\eta^\gamma - \bar{\eta}^- \left(\sqrt{\xi_W}\,e\frac{\delta G^-}{\delta\alpha^\gamma} \right)\eta^\gamma$$

$$= \bar{\eta}^+ \left[-\partial^2 - \xi_W m_W^2 - ie\overleftarrow{\partial^\mu} A_\mu - igc_W\overleftarrow{\partial^\mu} Z_\mu - \frac{1}{2}g\xi_W m_W(H + i\chi) \right]\eta^+$$

$$+\bar{\eta}^Z \left(igc_W\overleftarrow{\partial^\mu} W_\mu^- + \frac{1}{2}g\xi_Z m_Z\phi^- \right)\eta^+ + ie(\partial^\mu\bar{\eta}^\gamma)W_\mu^-\eta^+$$

$$+\bar{\eta}^- \left[-\partial^2 - \xi_W m_W^2 + ie\overleftarrow{\partial^\mu} A_\mu + igc_W\overleftarrow{\partial^\mu} Z_\mu - \frac{1}{2}g\xi_W m_W(H - i\chi) \right]\eta^-$$

$$+\bar{\eta}^Z \left(-igc_W\overleftarrow{\partial^\mu} W_\mu^+ + \frac{1}{2}g\xi_Z m_Z\phi^+ \right)\eta^- - ie(\partial^\mu\bar{\eta}^\gamma)W_\mu^+\eta^-$$

$$+\bar{\eta}^Z \left(-\partial^2 - \xi_Z m_Z^2 - \frac{g\xi_Z m_Z}{2c_W}H \right)\eta^Z + \bar{\eta}^+ \left(igc_W\overleftarrow{\partial^\mu} W_\mu^+ - \frac{g(c_W^2 - s_W^2)\xi_W m_W}{2c_W}\phi^+ \right)\eta^Z$$

$$+\bar{\eta}^- \left(-igc_W\overleftarrow{\partial^\mu} W_\mu^- - \frac{g(c_W^2 - s_W^2)\xi_W m_W}{2c_W}\phi^- \right)\eta^Z$$

$$-\bar{\eta}^\gamma\partial^2\eta^\gamma + \bar{\eta}^+(ie\overleftarrow{\partial^\mu} W_\mu^+ - e\xi_W m_W\phi^+)\eta^\gamma + \bar{\eta}^-(-ie\overleftarrow{\partial^\mu} W_\mu^- - e\xi_W m_W\phi^-)\eta^\gamma. \tag{137}$$

鬼粒子的质量为

$$m_{\eta^+} = m_{\eta^-} = \sqrt{\xi_W}\, m_W, \quad m_{\eta^Z} = \sqrt{\xi_Z}\, m_Z, \quad m_{\eta^\gamma} = 0. \tag{138}$$

下面给出 R_ξ 规范下的费曼规则。$\xi_i = 1$ 对应 Feynman-'t Hooft 规范，$\xi_i = 0$ 对应 Landau 规范，$\xi_W, \xi_Z \to \infty$ 对应幺正规范。在树图计算中，常取 $\xi_\gamma = 1$ 和 $\xi_W, \xi_Z \to \infty$。在圈图计算中，常取 $\xi_\gamma = \xi_W = \xi_Z = 1$。

传播子：

$$H \text{-----} H \quad = \frac{i}{p^2 - m_H^2 + i\varepsilon}$$

$$\chi \text{-----} \chi \quad = \frac{i}{p^2 - \xi_Z m_Z^2 + i\varepsilon}$$

$$\phi \text{-----} \phi \quad = \frac{i}{p^2 - \xi_W m_W^2 + i\varepsilon}$$

$$A_\mu \,\sim\sim\sim\, A_\nu \quad = \frac{-i}{p^2 + i\varepsilon}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}(1 - \xi_\gamma)\right]$$

$$Z_\mu \,\sim\sim\sim\, Z_\nu \quad = \frac{-i}{p^2 - m_Z^2 + i\varepsilon}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2 - \xi_Z m_Z^2}(1 - \xi_Z)\right]$$

$$W_\mu \,\sim\sim\sim\, W_\nu \quad = \frac{-i}{p^2 - m_W^2 + i\varepsilon}\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2 - \xi_W m_W^2}(1 - \xi_W)\right]$$

$$\eta^\gamma \cdots\cdots \eta^\gamma \quad = \frac{i}{p^2 + i\varepsilon}$$

$$\eta^Z \cdots\cdots \eta^Z \quad = \frac{i}{p^2 - \xi_Z m_Z^2 + i\varepsilon}$$

$$\eta^\pm \cdots\cdots \eta^\pm \quad = \frac{i}{p^2 - \xi_W m_W^2 + i\varepsilon}$$

标量玻色子三线性耦合：

$$
\begin{aligned}
&= -3i\frac{m_H^2}{v} \qquad\qquad\qquad\qquad = -i\frac{m_H^2}{v} \qquad\qquad\qquad\qquad = -i\frac{m_H^2}{v}\\
&= -6i\lambda v \qquad\qquad\qquad\qquad\quad\; = -2i\lambda v \qquad\qquad\qquad\qquad\; = -2i\lambda v
\end{aligned}
$$

标量玻色子四线性耦合：

$$
\begin{aligned}
&= -3i\frac{m_H^2}{v^2} \qquad\qquad\qquad\qquad = -i\frac{m_H^2}{v^2} \qquad\qquad\qquad\qquad = -3i\frac{m_H^2}{v^2}\\
&= -6i\lambda \qquad\qquad\qquad\qquad\quad\; = -2i\lambda \qquad\qquad\qquad\qquad\quad\; = -6i\lambda
\end{aligned}
$$

23

$$= -i\frac{m_H^2}{v^2}$$
$$= -2i\lambda$$

$$= -i\frac{m_H^2}{v^2}$$
$$= -2i\lambda$$

$$= -2i\frac{m_H^2}{v^2}$$
$$= -4i\lambda$$

Yukawa 耦合:

$$= -i\frac{m_f}{v}$$
$$= -i\frac{y_f}{\sqrt{2}}$$

$$= \frac{m_{\ell_i}}{v}\gamma_5$$
$$= \frac{y_{\ell_i}}{\sqrt{2}}\gamma_5$$

$$= -\frac{m_{u_i}}{v}\gamma_5$$
$$= -\frac{y_{u_i}}{\sqrt{2}}\gamma_5$$

$$= \frac{m_{d_i}}{v}\gamma_5$$
$$= \frac{y_{d_i}}{\sqrt{2}}\gamma_5$$

$$= i\frac{\sqrt{2}V_{ij}}{v}(m_{u_i}P_{\mathrm{L}} - m_{d_j}P_{\mathrm{R}})$$
$$= iV_{ij}(y_{u_i}P_{\mathrm{L}} - y_{d_j}P_{\mathrm{R}})$$

$$= -i\frac{\sqrt{2}V_{ji}^\dagger}{v}(m_{d_j}P_{\mathrm{L}} - m_{u_i}P_{\mathrm{R}})$$
$$= -iV_{ji}^\dagger(y_{d_j}P_{\mathrm{L}} - y_{u_i}P_{\mathrm{R}})$$

$$= -i\frac{\sqrt{2}m_{\ell_i}}{v}P_{\mathrm{R}}$$
$$= -iy_{\ell_i}P_{\mathrm{R}}$$

$$= -i\frac{\sqrt{2}m_{\ell_i}}{v}P_{\mathrm{L}}$$
$$= -iy_{\ell_i}P_{\mathrm{L}}$$

标量玻色子与电弱规范玻色子的三线性耦合:

$$= i\frac{gm_Z}{c_{\mathrm{W}}}g^{\mu\nu}$$
$$= i\frac{g^2v}{2c_{\mathrm{W}}^2}g^{\mu\nu}$$

$$= igm_Wg^{\mu\nu}$$
$$= i\frac{g^2v}{2}g^{\mu\nu}$$

$$= iem_Wg^{\mu\nu}$$
$$= i\frac{egv}{2}g^{\mu\nu}$$

$$= iem_Wg^{\mu\nu}$$
$$= i\frac{egv}{2}g^{\mu\nu}$$

24

$$= -igs_{\mathrm{W}}^2 m_Z g^{\mu\nu}$$
$$= -i\frac{g^2 s_{\mathrm{W}}^2 v}{2c_{\mathrm{W}}} g^{\mu\nu}$$
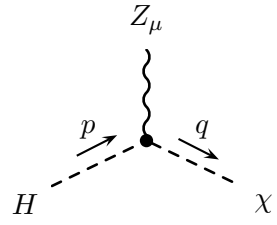
$$= -igs_{\mathrm{W}}^2 m_Z g^{\mu\nu}$$
$$= -i\frac{g^2 s_{\mathrm{W}}^2 v}{2c_{\mathrm{W}}} g^{\mu\nu}$$
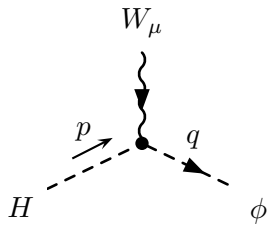
$$= ie(p+q)^\mu$$
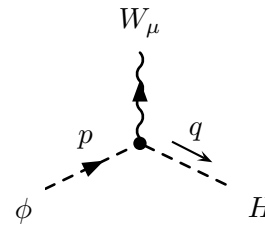
$$= i\frac{g(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)}{2c_{\mathrm{W}}}(p+q)^\mu$$
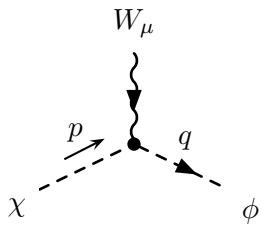
$$= -\frac{g}{2c_{\mathrm{W}}}(p+q)^\mu$$
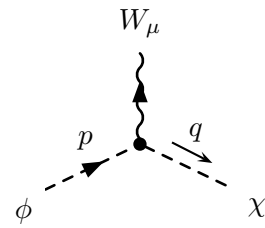
$$= i\frac{g}{2}(p+q)^\mu$$

$$= i\frac{g}{2}(p+q)^\mu$$
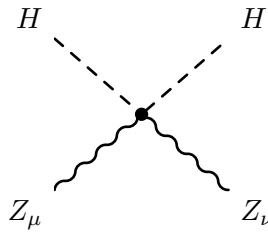
$$= -\frac{g}{2}(p+q)^\mu$$
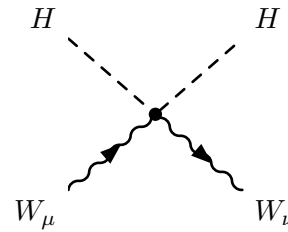
$$= \frac{g}{2}(p+q)^\mu$$
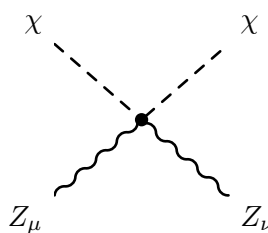
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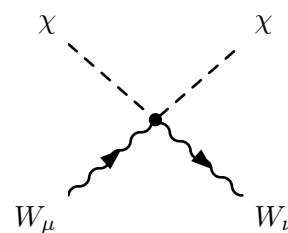
$$= i\frac{g^2}{2c_{\mathrm{W}}^2} g^{\mu\nu}$$
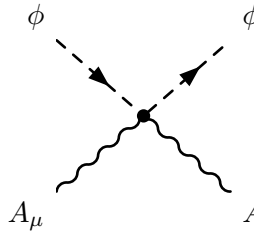
$$= i\frac{g^2}{2} g^{\mu\nu}$$
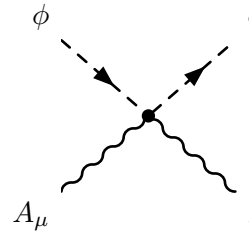
$$= i\frac{g^2}{2c_{\mathrm{W}}^2} g^{\mu\nu}$$
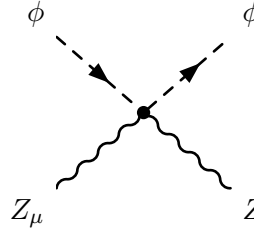
$$= i\frac{g^2}{2} g^{\mu\nu}$$
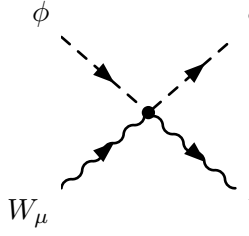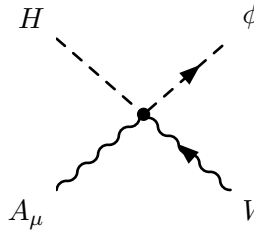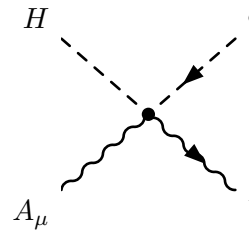
$$\phi \quad \phi$$

$$A_\mu \quad A_\nu \qquad = 2ie^2 g^{\mu\nu}$$

$$\phi \quad \phi$$

$$A_\mu \quad Z_\nu \qquad = i\frac{eg(c_W^2 - s_W^2)}{c_W}g^{\mu\nu}$$

$$\phi \quad \phi$$

$$Z_\mu \quad Z_\nu \qquad = i\frac{g^2(c_W^2 - s_W^2)^2}{2c_W^2}g^{\mu\nu}$$

$$\phi \quad \phi$$

$$W_\mu \quad W_\nu \qquad = i\frac{g^2}{2}g^{\mu\nu}$$

$$H \quad \phi$$

$$A_\mu \quad W_\nu \qquad = i\frac{eg}{2}g^{\mu\nu}$$

$$H \quad \phi$$

$$A_\mu \quad W_\nu \qquad = i\frac{eg}{2}g^{\mu\nu}$$

$$H \quad \phi$$

$$Z_\mu \quad W_\nu \qquad = -i\frac{g^2 s_W^2}{2c_W}g^{\mu\nu}$$

$$H \quad \phi$$

$$Z_\mu \quad W_\nu \qquad = -i\frac{g^2 s_W^2}{2c_W}g^{\mu\nu}$$

$$\chi \quad \phi$$

$$A_\mu \quad W_\nu \qquad = -\frac{eg}{2}g^{\mu\nu}$$

$$\chi \quad \phi$$

$$A_\mu \quad W_\nu \qquad = \frac{eg}{2}g^{\mu\nu}$$

$$\chi \quad \phi$$

$$Z_\mu \quad W_\nu \qquad = \frac{g^2 s_W^2}{2c_W}g^{\mu\nu}$$

$$\chi \quad \phi$$
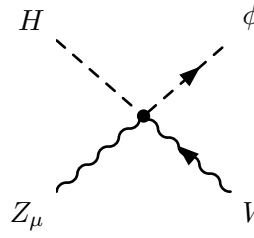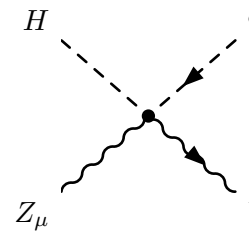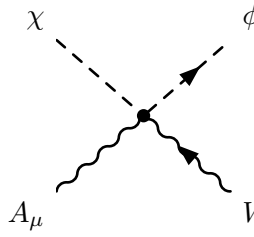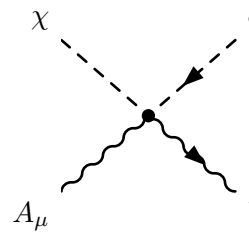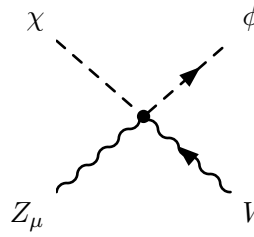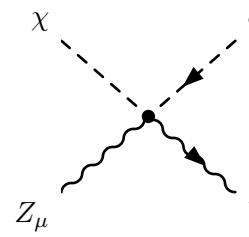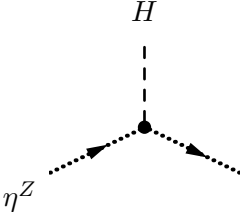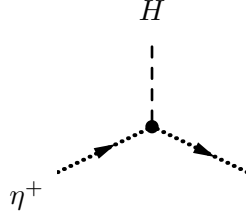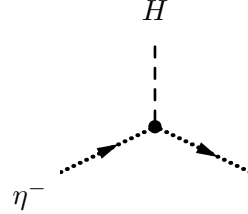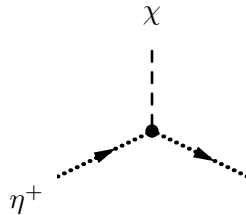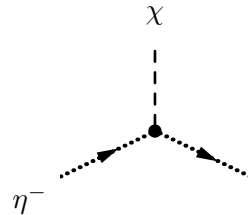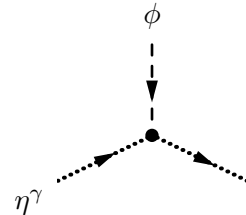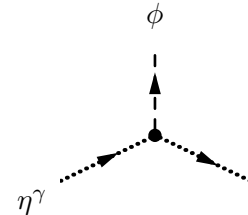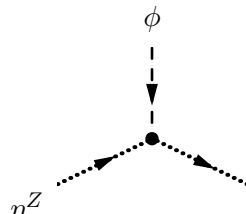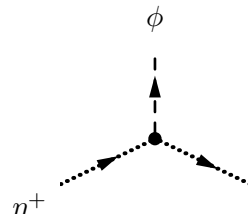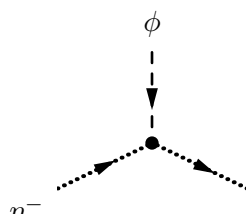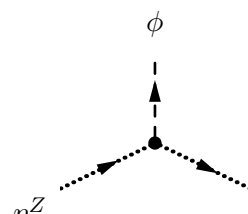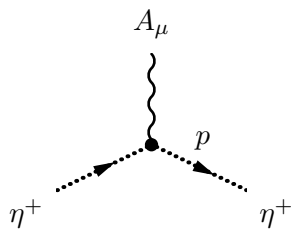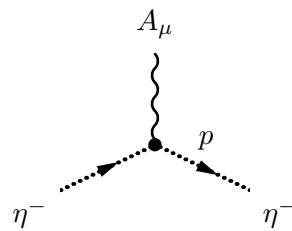
$$Z_\mu \quad W_\nu \qquad = -\frac{g^2 s_W^2}{2c_W}g^{\mu\nu}$$

鬼粒子与标量玻色子的耦合：

H

$$= -i\frac{g\xi_Z m_Z}{2c_{\mathrm{W}}}$$
$$= -i\frac{g^2\xi_Z v}{4c_{\mathrm{W}}^2}$$

η^Z η^Z

H

$$= -i\frac{g\xi_W m_W}{2}$$
$$= -i\frac{g^2\xi_W v}{4}$$

η^+ η^+

H

$$= -i\frac{g\xi_W m_W}{2}$$
$$= -i\frac{g^2\xi_W v}{4}$$

η^- η^-

χ

$$= \frac{g\xi_W m_W}{2}$$
$$= \frac{g^2\xi_W v}{4}$$

η^+ η^+

χ

$$= -\frac{g\xi_W m_W}{2}$$
$$= -\frac{g^2\xi_W v}{4}$$

η^- η^-

ϕ

$$= -ie\xi_W m_W$$
$$= -i\frac{eg\xi_W v}{2}$$

η^γ η^+

ϕ

$$= -ie\xi_W m_W$$
$$= -i\frac{eg\xi_W v}{2}$$

η^γ η^-

ϕ

$$= -i\frac{g(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)\xi_W m_W}{2c_{\mathrm{W}}}$$
$$= -i\frac{g^2(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)\xi_W v}{4c_{\mathrm{W}}}$$

η^Z η^+

ϕ

$$= i\frac{g\xi_Z m_Z}{2}$$
$$= i\frac{g^2\xi_Z v}{4c_{\mathrm{W}}}$$

η^+ η^Z

ϕ

$$= i\frac{g\xi_Z m_Z}{2}$$
$$= i\frac{g^2\xi_Z v}{4c_{\mathrm{W}}}$$

η^- η^Z

ϕ

$$= -i\frac{g(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)\xi_W m_W}{2c_{\mathrm{W}}}$$
$$= -i\frac{g^2(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)\xi_W v}{4c_{\mathrm{W}}}$$

η^Z η^-

鬼粒子与电弱规范玻色子的耦合：

A_μ

p $= iep^\mu$

η^+ η^+

A_μ

p $= -iep^\mu$

η^- η^-

$$Z_\mu, \eta^+, \eta^+, p \quad = igc_{\mathrm{W}}p^\mu$$

$$Z_\mu, \eta^-, \eta^-, p \quad = -igc_{\mathrm{W}}p^\mu$$

$$W_\mu, \eta^\gamma, \eta^+, p \quad = -iep^\mu$$

$$W_\mu, \eta^+, \eta^\gamma, p \quad = -iep^\mu$$

$$W_\mu, \eta^-, \eta^\gamma, p \quad = iep^\mu$$

$$W_\mu, \eta^\gamma, \eta^-, p \quad = iep^\mu$$

$$W_\mu, \eta^Z, \eta^+, p \quad = -igc_{\mathrm{W}}p^\mu$$

$$W_\mu, \eta^+, \eta^Z, p \quad = -igc_{\mathrm{W}}p^\mu$$

$$W_\mu, \eta^-, \eta^Z, p \quad = igc_{\mathrm{W}}p^\mu$$

$$W_\mu, \eta^Z, \eta^-, p \quad = igc_{\mathrm{W}}p^\mu$$

8 内外线一般费曼规则

标量玻色子传播子：

$$\cdots\cdots\cdots \underset{p\longrightarrow}{} = \frac{i}{p^2 - m^2 + i\varepsilon}$$

Dirac 费米子传播子：

$$\xrightarrow{\quad\quad} \underset{p}{} = \frac{i(\not{p} + m)}{p^2 - m^2 + i\varepsilon}$$

无质量规范玻色子（如光子）传播子：

$$\mu \;\rightsquigarrow\; \nu \underset{p\longrightarrow}{} = \frac{-ig_{\mu\nu}}{p^2 + i\varepsilon} \quad (\text{Feynman 规范})$$

$$\mu \;\rightsquigarrow\; \nu \underset{p\longrightarrow}{} = \frac{-i(g_{\mu\nu} - p_\mu p_\nu/p^2)}{p^2 + i\varepsilon} \quad (\text{Landau 规范})$$

宽度为 Γ 的有质量规范玻色子 (如 $W^\pm$ 和 Z) 传播子:

$$\mu \;\wwwww\; \nu \;\; \underset{p \longrightarrow}{} = \frac{-i(g_{\mu\nu} - p_\mu p_\nu / m^2)}{p^2 - m^2 + im\Gamma} \quad (\text{幺正规范})$$

$$\mu \;\wwwww\; \nu \;\; \underset{p \longrightarrow}{} = \frac{-ig_{\mu\nu}}{p^2 - m^2 + im\Gamma} \quad (\text{Feynman 规范})$$

标量玻色子外线:

$$\rangle\!-\!-\!-\!-\!- \;\; = 1 \quad (\text{初态或末态})$$

Dirac 费米子外线:

$$\underset{p}{\rangle\!\!\!-\!\!\leftarrow\!\!-} \;\; = u(p,s) \quad (\text{正粒子初态})$$

$$\underset{p}{\rangle\!\!\!-\!\!\rightarrow\!\!-} \;\; = \bar{u}(p,s) \quad (\text{正粒子末态})$$

$$\underset{\leftarrow p}{\rangle\!\!\!-\!\!\rightarrow\!\!-} \;\; = \bar{v}(p,s) \quad (\text{反粒子初态})$$

$$\underset{p \longrightarrow}{\rangle\!\!\!-\!\!\leftarrow\!\!-} \;\; = v(p,s) \quad (\text{反粒子末态})$$

在计算非极化截面时, 可利用自旋求和关系

$$\sum_s u(p,s)\bar{u}(p,s) = \slashed{p} + m, \quad \sum_s v(p,s)\bar{v}(p,s) = \slashed{p} - m. \tag{139}$$

矢量玻色子外线:

$$\underset{\longleftarrow p}{\rangle\!\!\wwwww} \; \mu \;\; = \varepsilon_\mu(p,\lambda) \quad (\text{初态})$$

$$\underset{p \longrightarrow}{\rangle\!\!\wwwww} \; \mu \;\; = \varepsilon_\mu^*(p,\lambda) \quad (\text{末态})$$

在计算非极化截面时, 若包含无质量矢量玻色子外线, 可作替换

$$\sum_\lambda \varepsilon_\mu^*(p,\lambda)\varepsilon_\nu(p,\lambda) \to -g_{\mu\nu}\,; \tag{140}$$

若包含有质量矢量玻色子外线, 可作替换

$$\sum_\lambda \varepsilon_\mu^*(p,\lambda)\varepsilon_\nu(p,\lambda) \to -g_{\mu\nu} + \frac{p_\mu p_\nu}{m^2}. \tag{141}$$

9 常用单位和标准模型参数

本节数据来自 Particle Data Group 发布的 2018 版 *Review of Particle Physics* [5]。

在有理化的自然单位制中, 光速、约化 Planck 常数和真空介电常数均取为 1, 即 $c = \hbar = \varepsilon_0 = 1$。从而, 速度没有量纲 (dimension); 长度量纲与时间量纲相同, 是能量量纲的倒数; 能量、质量和动量具有

相同的量纲；精细结构常数表达为 $\alpha = e^2/(4\pi)$，而单位电荷量 $e = \sqrt{4\pi\alpha}$ 是没有量纲的。可以将能量单位电子伏特 (eV) 视作上述有量纲物理量的基本单位。

单位间转换关系取为

$$1 = c = 2.99792458 \times 10^{10} \text{ cm} \cdot \text{s}^{-1}, \tag{142}$$

$$1 = \hbar = 6.582119514(40) \times 10^{-25} \text{ GeV} \cdot \text{s}, \tag{143}$$

$$1 = \hbar c = 1.973269788(12) \times 10^{-14} \text{ GeV} \cdot \text{cm}, \tag{144}$$

括号内数字代表测量值的 1σ 不确定度，由此可得

$$1 \text{ s} = 2.997925 \times 10^{10} \text{ cm}, \qquad 1 \text{ cm} = 3.335641 \times 10^{-11} \text{ s}, \tag{145}$$

$$1 \text{ s} = 1.519267 \times 10^{24} \text{ GeV}^{-1}, \quad 1 \text{ GeV}^{-1} = 6.582120 \times 10^{-25} \text{ s}, \tag{146}$$

$$1 \text{ cm} = 5.067731 \times 10^{13} \text{ GeV}^{-1}, \quad 1 \text{ GeV}^{-1} = 1.973270 \times 10^{-14} \text{ cm}, \tag{147}$$

$$1 \text{ cm}^2 = 2.568190 \times 10^{27} \text{ GeV}^{-2}, \quad 1 \text{ GeV}^{-2} = 3.893794 \times 10^{-28} \text{ cm}^2, \tag{148}$$

$$1 \text{ cm}^3 \cdot \text{s}^{-1} = 8.566558 \times 10^{16} \text{ GeV}^{-2}, \quad 1 \text{ GeV}^{-2} = 1.167330 \times 10^{-17} \text{ cm}^3 \cdot \text{s}^{-1}. \tag{149}$$

靶 (barn) 是散射截面的常用单位，记作 b，满足

$$1 \text{ b} = 10^{-24} \text{ cm}^2 = 10^9 \text{ nb} = 10^{12} \text{ pb} = 10^{15} \text{ fb} = 10^{18} \text{ ab}, \tag{150}$$

$$1 \text{ pb} = 10^{-36} \text{ cm}^2 = 2.568190 \times 10^{-9} \text{ GeV}^{-2}, \quad 1 \text{ GeV}^{-2} = 3.893794 \times 10^8 \text{ pb}. \tag{151}$$

Fermi 耦合常数是

$$G_{\text{F}} = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2}. \tag{152}$$

由树图阶关系式

$$\frac{G_{\text{F}}}{\sqrt{2}} = \frac{1}{2v^2} = \frac{g^2}{8m_{\text{W}}^2}, \tag{153}$$

可得 Higgs 场真空期待值为

$$v = (\sqrt{2}G_{\text{F}})^{-1/2} = 246.2197 \text{ GeV}. \tag{154}$$

在低能标 (Thomson 极限) 处，精细结构常数为

$$\alpha = 7.2973525664(17) \times 10^{-3} = \frac{1}{137.035999139(31)}; \tag{155}$$

在 $\overline{\text{MS}}$ 重整化方案（以 ^ 为标志）中，α^{-1} 跑动到 $\mu = m_Z$ 能标处的数值是

$$\widehat{\alpha}^{-1}(m_Z) = 127.955 \pm 0.010\,. \tag{156}$$

在 $\overline{\text{MS}}$ 方案中，$\mu = m_Z$ 能标处强耦合常数 $\alpha_{\text{s}} = g_{\text{s}}^2/(4\pi)$ 的数值为

$$\widehat{\alpha}_{\text{s}}(m_Z) = 0.1181 \pm 0.0011, \tag{157}$$

Weinberg 角 θ_{W} 的数值对应于

$$\widehat{s}_{\text{W}}^2 = \sin^2\widehat{\theta}_{\text{W}}(m_Z) = 0.23122 \pm 0.00004\,. \tag{158}$$

在标准模型中，光子、胶子和中微子没有质量，其它基本粒子的质量为

$$m_W = 80.379 \pm 0.012 \text{ GeV}, \qquad m_Z = 91.1876 \pm 0.0021 \text{ GeV}, \qquad m_H = 125.18 \pm 0.16 \text{ GeV}, \qquad (159)$$

$$m_e = 0.5109989461(31) \text{ MeV}, \qquad m_\mu = 105.6583745(24) \text{ MeV}, \qquad m_\tau = 1776.86 \pm 0.12 \text{ MeV}, \qquad (160)$$

$$m_u = 2.2^{+0.5}_{-0.4} \text{ MeV}, \qquad m_d = 4.7^{+0.5}_{-0.3} \text{ MeV}, \qquad m_s = 95^{+9}_{-3} \text{ MeV}, \qquad (161)$$

$$m_c = 1.67 \pm 0.07 \text{ GeV}, \qquad m_b = 4.78 \pm 0.06 \text{ GeV}, \qquad m_t = 173.0 \pm 0.4 \text{ GeV}. \qquad (162)$$

这里，u、d、s 夸克的质量是 $\mu \simeq 2$ GeV 能标处的流夸克质量 (current-quark mass)，其余粒子的质量均为极点质量 (pole mass)。c、b 夸克在 $\overline{\text{MS}}$ 方案中的跑动质量 (running mass) 为

$$\bar{m}_c(\bar{m}_c) = 1.275^{+0.025}_{-0.035} \text{ GeV}, \quad \bar{m}_b(\bar{m}_b) = 4.18^{+0.04}_{-0.03} \text{ GeV}. \qquad (163)$$

质子和中子的质量为

$$m_p = 938.2720813(58) \text{ MeV}, \quad m_n = 939.565413(6) \text{ MeV}. \qquad (164)$$

在电弱能标附近作领头阶计算时，可将单位电荷量 e 取为

$$e = \sqrt{4\pi\widehat{\alpha}(m_Z)} = 0.3133836, \qquad (165)$$

将强耦合常数 g_s 取为

$$g_\text{s} = \sqrt{4\pi\widehat{\alpha}_\text{s}(m_Z)} = 1.218232. \qquad (166)$$

从树图阶关系计算 Higgs 场四线性耦合常数 λ 和 Yukawa 耦合常数 y_t、y_b、y_τ、y_c，得

$$\lambda = \frac{m_H^2}{2v^2} = 0.1292393, \quad y_t = \frac{\sqrt{2}m_t}{v} = 0.9936613, \quad y_b = \frac{\sqrt{2}m_b}{v} = 2.745492 \times 10^{-2}, \qquad (167)$$

$$y_\tau = \frac{\sqrt{2}m_\tau}{v} = 1.020576 \times 10^{-2}, \quad y_c = \frac{\sqrt{2}m_c}{v} = 9.591991 \times 10^{-3}. \qquad (168)$$

耦合常数 g 和 g' 有以下两种取值方式。

1. 根据树图阶关系 $\sin^2\theta_\text{W} = 1 - m_W^2/m_Z^2$ 计算 Weinberg 角，得

$$s_\text{W}^2 = 1 - \frac{m_W^2}{m_Z^2} = 0.2230132, \quad c_\text{W}^2 = 1 - s_\text{W}^2 = 0.7769868, \qquad (169)$$

$$s_\text{W} = \sqrt{s_\text{W}^2} = 0.4722428, \quad c_\text{W} = \sqrt{c_\text{W}^2} = 0.8814685, \qquad (170)$$

故

$$g = \frac{e}{s_\text{W}} = 0.6636071, \quad g' = \frac{e}{c_\text{W}} = 0.3555245. \qquad (171)$$

2. 根据 $\overline{\text{MS}}$ 方案中 Weinberg 角的数值 (158) 计算 g 和 g'，得

$$c_\text{W}^2 = 1 - \widehat{s}_\text{W}^2 = 0.76878, \quad s_\text{W} = \sqrt{\widehat{s}_\text{W}^2} = 0.4808534, \quad c_\text{W} = \sqrt{c_\text{W}^2} = 0.8768010, \qquad (172)$$

$$g = \frac{e}{s_\text{W}} = 0.6517238, \quad g' = \frac{e}{c_\text{W}} = 0.3574170. \qquad (173)$$

CKM 矩阵分量 V_{ij} 之模的测量值为

$$|V_{ij}| = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}. \tag{174}$$

如果仅仅近似地考虑 Cabibbo 转动角 θ_{C}，有

$$V_{ij} \simeq \begin{pmatrix} \cos\theta_{\mathrm{C}} & \sin\theta_{\mathrm{C}} & \\ -\sin\theta_{\mathrm{C}} & \cos\theta_{\mathrm{C}} & \\ & & 1 \end{pmatrix}, \quad \sin\theta_{\mathrm{C}} = |V_{12}| = 0.22452. \tag{175}$$

参考文献

[1] M. E. Peskin and D. V. Schroeder, "An Introduction to Quantum Field Theory," Reading, USA: Addison-Wesley (1995), 842 pages.

[2] T. P. Cheng and L. F. Li, "Gauge Theory of Elementary Particle Physics," Oxford, UK: Clarendon (1984), 536 pages.

[3] A. Denner, "Techniques for calculation of electroweak radiative corrections at the one loop level and results for W physics at LEP-200," Fortsch. Phys. **41**, 307 (1993) [arXiv:0709.1075 [hep-ph]].

[4] 杜东生，杨茂志，《粒子物理导论》，中国北京：科学出版社 (2014)，402 页。

[5] M. Tanabashi *et al.* [Particle Data Group], "Review of Particle Physics," Phys. Rev. D **98**, 030001 (2018).