TÉCNICO LISBOA

Advanced Quantum Field Theory

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Appendix D

Feynman Rules for the Standard Model

D.1 Introduction

To do actual calculations it is very important to have all the Feynman rules with consistent conventions. In this Appendix we will give the complete Feynman rules for the Standard Model in the general R_ξ gauge.

D.2 The Standard Model

One of the most difficult problems in having a consistent set of of Feynman rules are the conventions. We give here those that are important for building the SM. We will separate them by gauge group.

D.2.1 Gauge Group $SU(3)_c$

Here the important conventions are for the field strengths and the covariant derivatives. We have

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g f^{abc} G^b_\mu G^c_\nu, \quad a = 1, \ldots, 8 \tag{D.1}$$

where f^{abc} are the group structure constants, satisfying

$$\left[T^a, T^b\right] = i f^{abc} T^c \tag{D.2}$$

and T^a are the generators of the group. The covariant derivative of a (quark) field q in some representation T^a of the gauge group is given by

$$D_\mu q = \left(\partial_\mu - i\, g\, G^a_\mu T^a\right) q \tag{D.3}$$

In QCD the quarks are in the fundamental representation and $T^a = \lambda^a/2$ where λ^a are the Gell-Mann matrices. A gauge transformation is given by a matrix

$$U = e^{-iT^a \alpha^a} \tag{D.4}$$

and the fields transform as

$$q \to e^{-iT^a\alpha^a} q \qquad\qquad \delta q = -iT^a\alpha^a q$$

$$G^a_\mu T^a \to U G^a_\mu T^a U^{-1} - \frac{i}{g}\partial_\mu U U^{-1} \qquad\qquad \delta G^a_\mu = -\frac{1}{g}\partial_\mu\alpha^a + f^{abc}\alpha^b G^c_\mu \tag{D.5}$$

where the second column is for infinitesimal transformations. With these definitions one can verify that the covariant derivative transforms like the field itself,

$$\delta(D_\mu q) = -i\,T^a\alpha^a(D_\mu q) \tag{D.6}$$

ensuring the gauge invariance of the Lagrangian.

D.2.2 Gauge Group $SU(2)_L$

This is similar to the previous case. We have

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g\epsilon^{abc}W^b_\mu W^c_\nu, \quad a = 1,\ldots,3 \tag{D.7}$$

where, for the fundamental representation of $SU(2)_L$ we have $T^a = \sigma^a/2$ and ϵ^{abc} is the completely anti-symmetric tensor in 3 dimensions. The covariant derivative for any field ψ_L transforming non-trivially under this group is,

$$D_\mu\psi_L = \left(\partial_\mu - i\,g\,W^a_\mu T^a\right)\psi_L \tag{D.8}$$

D.2.3 Gauge Group $U(1)_Y$

In this case the group is abelian and we have

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \tag{D.9}$$

with the covariant derivative given by

$$D_\mu\psi_R = \left(\partial_\mu + i\,g'\,Y\,B_\mu\right)\psi_R \tag{D.10}$$

where Y is the hypercharge of the field. Notice the different sign convention between Eq. (D.8) and Eq. (D.9). This is to have the usual definition[1]

$$Q = T_3 + Y\ . \tag{D.12}$$

It is useful to write the covariant derivative in terms of the mass eigenstates A_μ and Z_μ. These are defined by the relations,

$$\left\{\begin{array}{l} W^3_\mu = Z_\mu\cos\theta_W - A_\mu\sin\theta_W \\ B_\mu = Z_\mu\sin\theta_W + A_\mu\cos\theta_W \end{array}\right. , \quad \left\{\begin{array}{l} Z_\mu = W^3_\mu\cos\theta_W + B_\mu\sin\theta_W \\ A_\mu = -W^3_\mu\sin\theta_W + B_\mu\cos\theta_W \end{array}\right. . \tag{D.13}$$

[1] For this to be consistent one must also have, under hypercharge transformations, for a field of hypercharge Y,

$$\psi' = e^{+iY\alpha_Y}\psi, \quad B'_\mu = B_\mu - \frac{1}{g'}\partial_\mu\alpha_Y\ . \tag{D.11}$$

This is important when finding the ghost interactions. It would have been possible to have a minus sign in Eq. (D.10), with a definition $\theta_W \to \theta_W + \pi$. This would also mean reversing the sign in the exponent of the hypercharge transformation in Eq. (D.11) maintaining the similarity with Eq. (D.5).

Field	ℓ_L	ℓ_R	ν_L	u_L	d_L	u_R	d_R	ϕ^+	ϕ^0
T_3	$-\frac{1}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
Y	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$\frac{1}{6}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
Q	-1	-1	0	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	1	0

Table D.1: Values of T_3^f, Q and Y for the SM particles.

For a field ψ_L, with hypercharge Y, we get,

$$\begin{aligned} D_\mu \psi_L &= \left[\partial_\mu - i\frac{g}{\sqrt{2}}\left(\tau^+ W^+_\mu + \tau^- W^-_\mu\right) - i\frac{g}{2}\tau_3 W^3_\mu + ig' Y B_\mu\right]\psi_L \\ &= \left[\partial_\mu - i\frac{g}{\sqrt{2}}\left(\tau^+ W^+_\mu + \tau^- W^-_\mu\right) + ie\,Q\,A_\mu - i\frac{g}{\cos\theta_W}\left(\frac{\tau_3}{2} - Q\,\sin^2\theta_W\right) Z_\mu\right]\psi_L \end{aligned} \tag{D.14}$$

where, as usual, $\tau^\pm = (\tau_1 \pm i\tau_2)/2$ and the charge operator is defined by

$$Q = \begin{bmatrix} \frac{1}{2} + Y & 0 \\ 0 & -\frac{1}{2} + Y \end{bmatrix} , \tag{D.15}$$

and we have used the relations,

$$e = g \sin\theta_W = g' \cos\theta_W \,, \tag{D.16}$$

and the usual definition,

$$W^\pm_\mu = \frac{W^1_\mu \mp i\, W^2_\mu}{\sqrt{2}} \,. \tag{D.17}$$

For a singlet of $SU(2)_L$, ψ_R we have,

$$\begin{aligned} D_\mu \psi_R &= \left[\partial_\mu + ig' Y B_\mu\right]\psi_R \\ &= \left[\partial_\mu + ie\,Q\,A_\mu + i\frac{g}{\cos\theta_W} Q\,\sin^2\theta_W Z_\mu\right]\psi_R \,. \end{aligned} \tag{D.18}$$

We collect in Table D.1 the quantum number of the SM particles.

D.2.4 The Gauge Field Lagrangian

For completeness we write the gauge field Lagrangian. We have

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \tag{D.19}$$

where the field strengths are given in Eqs. (D.1), and (D.9).

D.2.5 The Fermion Fields Lagrangian

Here we give the kinetic part and gauge interaction, leaving the Yukawa interaction for a next section. We have

$$\mathcal{L}_{\text{Fermion}} = \sum_{\text{quarks}} i\overline{q}\gamma^\mu D_\mu q + \sum_{\psi_L} i\overline{\psi_L}\gamma^\mu D_\mu \psi_L + \sum_{\psi_R} i\overline{\psi_R}\gamma^\mu D_\mu \psi_R \tag{D.20}$$

where the covariant derivatives are obtained with the rules in Eqs. (D.3), (D.14) and (D.18).

D.2.6 The Higgs Lagrangian

In the SM we use an Higgs doublet with the following assignments,

$$\Phi = \begin{bmatrix} \phi^+ \\ \dfrac{v + H + i\varphi_Z}{\sqrt{2}} \end{bmatrix} \tag{D.21}$$

The hypercharge of this doublet is 1/2 and therefore the covariant derivative reads

$$\begin{aligned} D_\mu\Phi &= \left[\partial_\mu - i\frac{g}{\sqrt{2}}\left(\tau^+W^+_\mu + \tau^-W^-_\mu\right) - i\frac{g}{2}\tau_3 W^3_\mu + i\frac{g'}{2}B_\mu\right]\Phi \\ &= \left[\partial_\mu - i\frac{g}{\sqrt{2}}\left(\tau^+W^+_\mu \tau^-W^-_\mu\right) + ie\,Q\,A_\mu - i\frac{g}{\cos\theta_W}\left(\frac{\tau_3}{2} - Q\,\sin^2\theta_W\right)Z_\mu\right]\Phi \end{aligned} \tag{D.22}$$

The Higgs Lagrangian is then

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\Phi)^\dagger D_\mu\Phi + \mu^2\Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2 \tag{D.23}$$

If we expand this Lagrangian we find the following terms

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \cdots &+ \frac{1}{8}g^2v^2W^3_\mu W^{\mu 3} + \frac{1}{8}g'^2v^2B_\mu B^\mu + \frac{1}{4}gg'v^2W^3_\mu B^\mu + \frac{1}{4}g^2v^2W^+_\mu W^{-\mu} \\ &+ \frac{1}{2}v\,\partial^\mu\varphi_Z\left(g'B_\mu + gW^3_\mu\right) + \frac{i}{2}gvW^-_\mu\partial^\mu\varphi^+ - \frac{i}{2}gvW^+_\mu\partial^\mu\varphi^- \end{aligned} \tag{D.24}$$

The first three terms give, after diagonalization, a massless field, the photon, and a massive one, the Z, with the relations given in Eq. (D.13), while the fourth gives the mass to the charged $W^\pm_\mu$ boson. Using Eq. (D.13) we get,

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \cdots &+ \frac{1}{2}M_Z^2 Z_\mu Z^\mu + M_W^2 W^+_\mu W^{-\mu} \\ &+ M_Z Z_\mu\partial^\mu\varphi_Z + iM_W\left(W^-_\mu\partial^\mu\varphi^+ - W^+_\mu\partial^\mu\varphi^-\right) \end{aligned} \tag{D.25}$$

where

$$M_W = \frac{1}{2}gv, \quad M_Z = \frac{1}{\cos\theta_W}\frac{1}{2}gv = \frac{1}{\cos\theta_W}M_W \tag{D.26}$$

By looking at Eq. (D.25) we realize that besides finding a realistic spectra for the gauge bosons, we also got a problem. In fact the terms in the last line are quadratic in the fields and complicate the definition of the propagators. We now see how one can use the needed gauge fixing to solve also this problem.

D.2.7 The Yukawa Lagrangian

Now we have to spell out the interaction between the fermions and the Higgs doublet that after spontaneous symmetry breaking gives masses to the elementary fermions. We have,

$$\mathcal{L}_{\text{Yukawa}} = - Y_l \, \overline{L} \, \Phi \; \ell_R - Y_d \, \overline{Q} \, \Phi \; d_R - Y_u \, \overline{Q} \, \widetilde{\Phi} \; u_R + \text{h.c.} \tag{D.27}$$

where sum is implied over generations, L (Q) are the lepton (quark) doublets and,

$$\widetilde{\Phi} = i \, \sigma_2 \Phi^* = \begin{bmatrix} \dfrac{v + H - i\varphi_Z}{\sqrt{2}} \\ -\varphi^- \end{bmatrix} \tag{D.28}$$

D.2.8 The Gauge Fixing

As it is well known, we have to gauge fix the gauge part of the Lagrangian to be able to define the propagators. We will use a generalization of the class of Lorenz gauges, the so-called R_ξ gauges. With this choice the gauge fixing Lagrangian reads

$$\mathcal{L}_{\text{GF}} = -\frac{1}{2\xi} F_G^2 - \frac{1}{2\xi} F_A^2 - \frac{1}{2\xi} F_Z^2 - \frac{1}{\xi} F_- F_+ \tag{D.29}$$

where

$$\begin{aligned} F_G^a =& \partial^\mu G_\mu^a, \quad F_A = \partial^\mu A_\mu, \quad F_Z = \partial^\mu Z_\mu - \xi M_Z \varphi_Z \\ F_+ =& \partial^\mu W_\mu^+ - i\xi M_W \varphi^+, \quad F_- = \partial^\mu W_\mu^- + i\xi M_W \varphi^- \end{aligned} \tag{D.30}$$

One can easily verify that with these definitions we cancel the quadratic terms in Eq. (D.25).

D.2.9 The Ghost Lagrangian

The last piece in writing the SM Lagrangian is the ghost Lagrangian. As it is well known, this is given by the Fadeev-Popov prescription,

$$\begin{aligned} \mathcal{L}_{\text{Ghost}} =& \sum_{i=1}^{4} \left[\overline{c}_+ \frac{\partial(\delta F_+)}{\partial \alpha^i} + \overline{c}_- \frac{\partial(\delta F_+)}{\partial \alpha^i} + \overline{c}_Z \frac{\partial(\delta F_Z)}{\partial \alpha^i} + \overline{c}_A \frac{\partial(\delta F_A)}{\partial \alpha^i} \right] c_i \\ &+ \sum_{a,b=1}^{8} \overline{\omega}^a \frac{\partial(\delta F_G^a)}{\partial \beta^b} \omega^b \end{aligned} \tag{D.31}$$

where we have denoted by ω^a the ghosts associated with the $SU(3)_c$ transformations defined by,

$$U = e^{-iT^a \beta^a}, \quad a = 1, \ldots, 8 \tag{D.32}$$

and by $c_\pm, c_A, c_Z$ the electroweak ghosts associated with the gauge transformations,

$$U = e^{-iT^a \alpha^a}, \quad a = 1, \ldots, 3, \quad U = e^{iY \alpha^4} \tag{D.33}$$

For completeness we write here the gauge transformations of the gauge fixing terms needed to find the Lagrangian in Eq. (D.31). It is convenient to redefine the parameters as

$$\begin{aligned}\alpha^{\pm} =& \frac{\alpha^1 \mp \alpha^2}{\sqrt{2}}\\ \alpha_Z =& \alpha^3 \cos\theta_W + \alpha^4 \sin\theta_W\\ \alpha_A =& -\alpha^3 \sin\theta_W + \alpha^4 \cos\theta_W\end{aligned} \tag{D.34}$$

We then get

$$\begin{aligned}\delta F_G^a =& -\partial_\mu \beta^a + g_s f^{abc} \beta^b G_\mu^c\\ \delta F_A =& -\partial_\mu \alpha_A\\ \delta F_Z =& \partial_\mu (\delta Z^\mu) - M_Z \delta\varphi_Z\\ \delta F_+ =& \partial_\mu (\delta W_\mu^+) - i M_W \delta\varphi^+\\ \delta F_- =& \partial_\mu (\delta W_\mu^-) + i M_W \delta\varphi^-\end{aligned} \tag{D.35}$$

Using the explicit form of the gauge transformations we can finally find the missing pieces,

$$\delta Z_\mu = -\partial_\mu \alpha_Z + ig\cos\theta_W \left(W_\mu^+ \alpha^- - W_\mu^- \alpha^+\right) \tag{D.36}$$

$$\begin{aligned}\delta W_\mu^+ =& -\partial_\mu \alpha^+ + ig\left[\alpha^+ \left(Z_\mu \cos\theta_W - A_\mu \sin\theta_w\right) - \left(\alpha_Z \cos\theta_w - \alpha_A \sin\theta_W\right) W_\mu^+\right]\\ \delta W_\mu^- =& -\partial_\mu \alpha^- - ig\left[\alpha^- \left(Z_\mu \cos\theta_W - A_\mu \sin\theta_w\right) - \left(\alpha_Z \cos\theta_w - \alpha_A \sin\theta_W\right) W_\mu^-\right]\end{aligned}$$

and

$$\begin{aligned}\delta\varphi_Z =& -\frac{1}{2} g\left(\alpha^- \varphi^+ + \alpha^+ \varphi^-\right) + \frac{g}{2\cos\theta_W} \alpha_Z (v+H)\\ \delta\varphi^+ =& -i\,\frac{g}{2}(v+H+i\varphi_Z)\alpha^+ - i\,\frac{g}{2}\frac{\cos 2\theta_W}{\cos\theta_W}\varphi^+\alpha_Z + ie\,\varphi^+\alpha_A\\ \delta\varphi^- =& i\,\frac{g}{2}(v+H-i\varphi_Z)\alpha^- + i\,\frac{g}{2}\frac{\cos 2\theta_W}{\cos\theta_W}\varphi^-\alpha_Z - ie\,\varphi^-\alpha_A\end{aligned} \tag{D.37}$$

D.2.10 The Complete SM Lagrangian

Finally the complete Lagrangian for the Standard Model is obtained putting together all the pieces. We have,

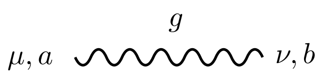
$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Fermion} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm Ghost} \tag{D.38}$$

where the different terms were given in Eqs. (D.19), (D.20), (D.23), (D.27), (D.29), (D.31).

D.3 The Feynman Rules for QCD

We give separately the Feynman Rules for QCD and the electroweak part of the Standard Model.

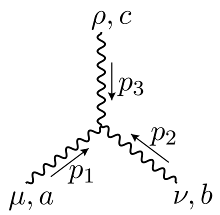
D.3.1 Propagators



$$-i\delta_{ab}\left[\frac{g_{\mu\nu}}{k^2+i\epsilon}-(1-\xi)\frac{k_\mu k_\nu}{(k^2)^2}\right] \tag{D.39}$$

$$\delta_{ab}\,\frac{i}{k^2+i\epsilon} \tag{D.40}$$

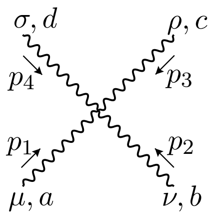
D.3.2 Triple Gauge Interactions



$$\begin{aligned} g f^{abc}[\ & g^{\mu\nu}(p_1-p_2)^\rho + g^{\nu\rho}(p_2-p_3)^\mu \\ & + g^{\rho\mu}(p_3-p_1)^\nu] \\ & p_1+p_2+p_3=0 \end{aligned} \tag{D.41}$$

D.3.3 Quartic Gauge Interactions

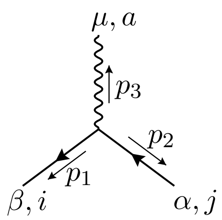
ii) Vértice quártico dos bosões de gauge



$$\begin{aligned} -ig^2\Big[\ & f_{eab}f_{ecd}(g_{\mu\rho}g_{\nu\sigma}-g_{\mu\sigma}g_{\nu\rho}) \\ & + f_{eac}f_{edb}(g_{\mu\sigma}g_{\rho\nu}-g_{\mu\nu}g_{\rho\sigma}) \\ & + f_{ead}f_{ebc}(g_{\mu\nu}g_{\rho\sigma}-g_{\mu\rho}g_{\nu\sigma})\Big] \end{aligned} \tag{D.42}$$

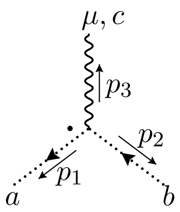
$$p_1+p_2+p_3+p_4=0$$

D.3.4 Fermion Gauge Interactions



$$ig(\gamma^\mu)_{\beta\alpha}T^a_{ij} \tag{D.43}$$

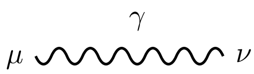
D.3.5 Ghost Interactions



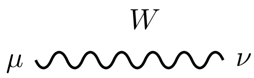
$$g\ C^{abc} p_1^{\mu} \qquad p_1 + p_2 + p_3 = 0 \tag{D.44}$$

D.4 The Feynman Rules for the Electroweak Theory

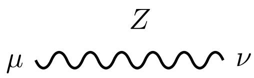
D.4.1 Propagators



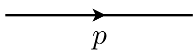
$$-i\left[\frac{g_{\mu\nu}}{k^2+i\epsilon} - (1-\xi)\frac{k_\mu k_\nu}{(k^2)^2}\right] \tag{D.45}$$



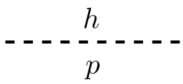
$$\frac{-ig_{\mu\nu}}{k^2 - M_W^2 + i\epsilon} \tag{D.46}$$



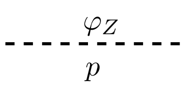
$$\frac{-ig_{\mu\nu}}{k^2 - M_Z^2 + i\epsilon} \tag{D.47}$$



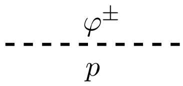
$$\frac{i(\not p + m_f)}{p^2 - m_f^2 + i\epsilon} \tag{D.48}$$



$$\frac{i}{p^2 - M_h^2 + i\epsilon} \tag{D.49}$$

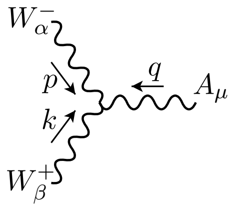


$$\frac{i}{p^2 - \xi m_Z^2 + i\epsilon} \tag{D.50}$$

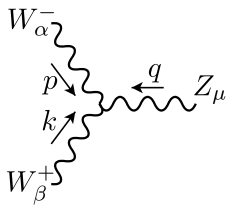


$$\frac{i}{p^2 - \xi m_W^2 + i\epsilon} \tag{D.51}$$

D.4.2 Triple Gauge Interactions

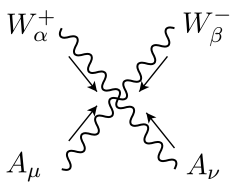


$$-ie\left[g_{\alpha\beta}(p-k)_\mu + g_{\beta\mu}(k-q)_\alpha + g_{\mu\alpha}(q-p)_\beta\right] \tag{D.52}$$

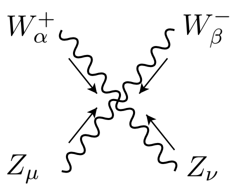


$$ig\cos\theta_W\left[g_{\alpha\beta}(p-k)_\mu + g_{\beta\mu}(k-q)_\alpha + g_{\mu\alpha}(q-p)_\beta\right] \tag{D.53}$$

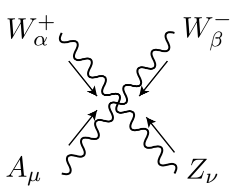
D.4.3 Quartic Gauge Interactions



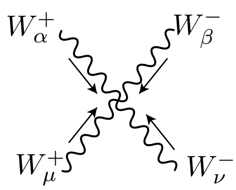
$$-ie^2\left[2g_{\alpha\beta}g_{\mu\mu} - g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu}\right] \tag{D.54}$$



$$-ig^2\ \cos^2\theta_W\left[2g_{\alpha\beta}g_{\mu\nu} - g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu}\right] \tag{D.55}$$

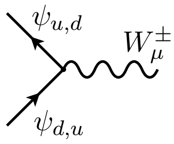


$$ieg\cos\theta_W\left[2g_{\alpha\beta}g_{\mu\nu} - g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu}\right] \tag{D.56}$$



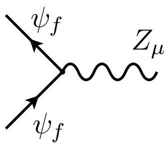
$$ig^2\left[2g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\beta}g_{\mu\nu} - g_{\alpha\nu}g_{\beta\mu}\right] \tag{D.57}$$

D.4.4 Charged Current Interaction

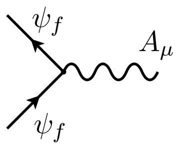


$$i\frac{g}{\sqrt{2}}\gamma_\mu\frac{1-\gamma_5}{2} \tag{D.58}$$

D.4.5 Neutral Current Interaction



$$i\frac{g}{\cos\theta_W}\gamma_\mu\left(g_V^f - g_A^f\gamma_5\right)$$

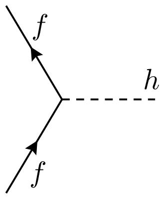


$$-ieQ_f\gamma_\mu \tag{D.59}$$

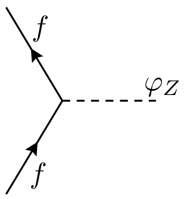
where

$$g_V^f = \frac{1}{2}T_f^3 - Q_f\sin^2\theta_W, \quad g_A^f = \frac{1}{2}T_f^3\ . \tag{D.60}$$

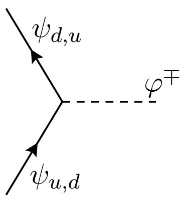
D.4.6 Fermion-Higgs and Fermion-Goldstone Interactions



$$-i\,\frac{g}{2}\,\frac{m_f}{m_W} \tag{D.61}$$

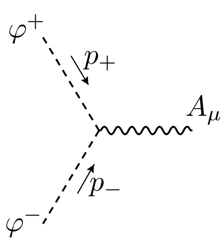


$$-g\,T_f^3\,\frac{m_f}{m_W}\,\gamma_5 \tag{D.62}$$

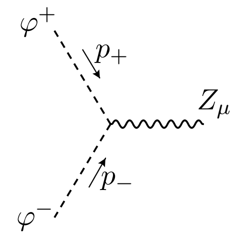


$$i\frac{g}{\sqrt{2}}\left(\frac{m_u}{m_W}P_{R,L} - \frac{m_d}{m_W}P_{L,R}\right) \tag{D.63}$$

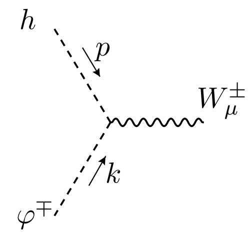
D.4.7 Triple Higgs-Gauge and Goldstone-Gauge Interactions



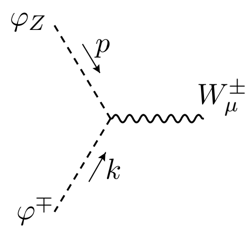
$$-i\,e\,\left(p_+ - p_-\right)_\mu \tag{D.64}$$



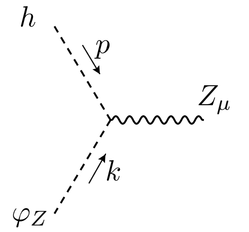
$$i\,g\,\frac{\cos 2\theta_W}{2\cos\theta_W}\,(p_+ - p_-)_\mu \tag{D.65}$$



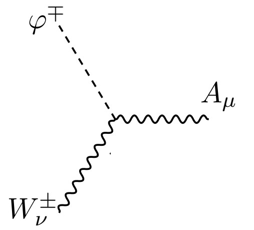
$$\mp\frac{i}{2}\,g\;(k-p)_\mu \tag{D.66}$$



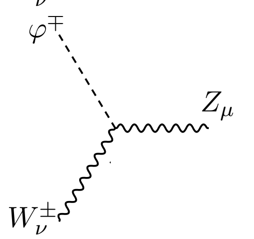
$$\frac{g}{2}\;(k-p)_\mu \tag{D.67}$$



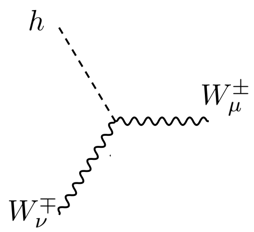
$$\frac{g}{2\cos\theta}\;(k-p)_\mu \tag{D.68}$$



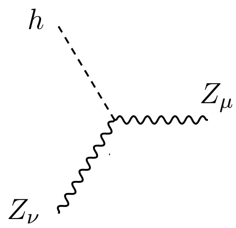
$$-ie\,m_W\,g_{\mu\nu} \tag{D.69}$$



$$-ig\,m_Z\,\sin^2\theta_W\,g_{\mu\nu} \tag{D.70}$$

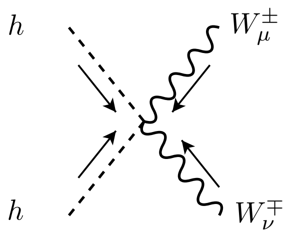


$$ig\,m_W\,g_{\mu\nu} \tag{D.71}$$

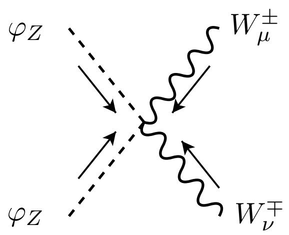


$$i\,\frac{g}{\cos\theta_W}\,m_Z\,g_{\mu\nu} \tag{D.72}$$

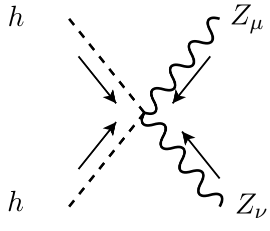
D.4.8 Quartic Higgs-Gauge and Goldstone-Gauge Interactions



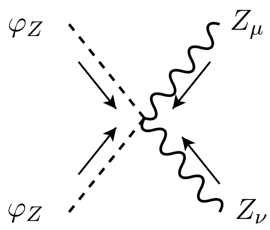
$$\frac{i}{2}\,g^2\,g_{\mu\nu} \tag{D.73}$$



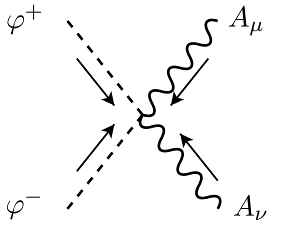
$$\frac{i}{2}\,g^2\,g_{\mu\nu} \tag{D.74}$$



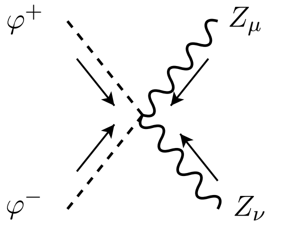
$$\frac{i}{2}\frac{g^2}{\cos^2\theta_W}g_{\mu\nu} \tag{D.75}$$



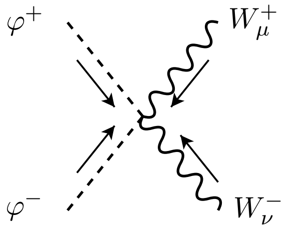
$$\frac{i}{2}\frac{g^2}{\cos^2\theta_W}g_{\mu\nu} \tag{D.76}$$



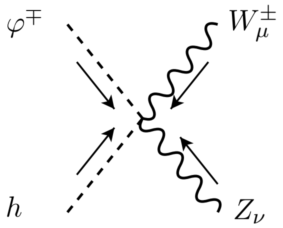
$$2i\, e^2\, g_{\mu\nu} \tag{D.77}$$



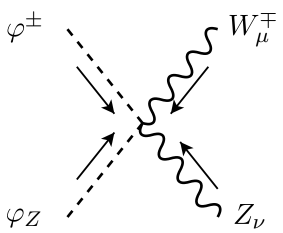
$$\frac{i}{2}\left(\frac{g\cos 2\theta_W}{\cos\theta_W}\right)^2 g_{\mu\nu} \tag{D.78}$$



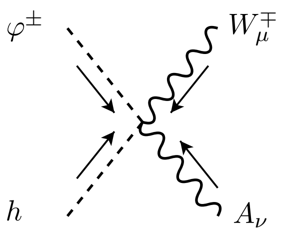
$$\frac{i}{2}\, g^2\, g_{\mu\nu} \tag{D.79}$$



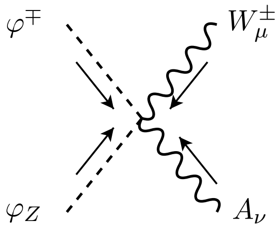
$$-i\, g^2\, \frac{\sin^2\theta_W}{2\cos\theta_W}\, g_{\mu\nu} \tag{D.80}$$



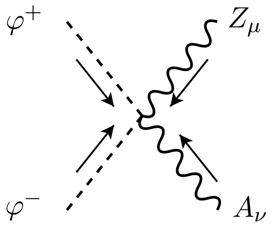
$$\mp\, g^2\, \frac{\sin^2\theta_W}{2\cos\theta_W}\, g_{\mu\nu} \tag{D.81}$$



$$-\frac{i}{2}\, eg\, g_{\mu\nu} \tag{D.82}$$

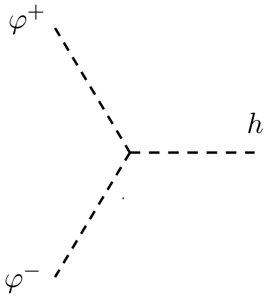


$$\pm\frac{1}{2}\,eg\,g_{\mu\nu} \tag{D.83}$$

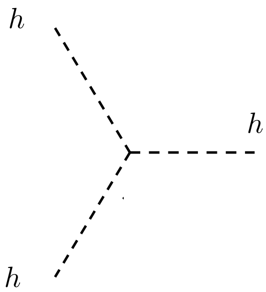


$$-i\,eg\,\frac{\cos 2\theta_W}{\cos\theta_W}g_{\mu\nu} \tag{D.84}$$

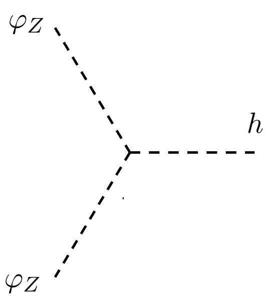
D.4.9 Triple Higgs and Goldstone Interactions



$$-\frac{i}{2}\,g\,\frac{m_h^2}{m_W} \tag{D.85}$$

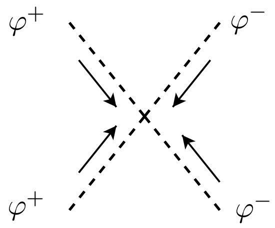


$$-\frac{3}{2}\,i\,g\frac{m_h^2}{m_W} \tag{D.86}$$

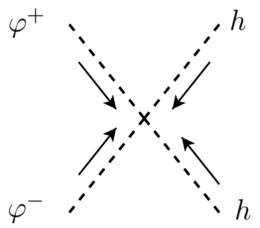


$$-\frac{i}{2}\,g\frac{m_h^2}{m_W} \tag{D.87}$$

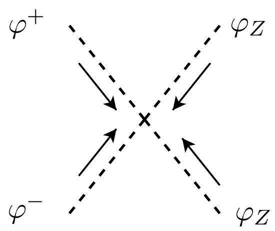
D.4.10 Quartic Higgs and Goldstone Interactions



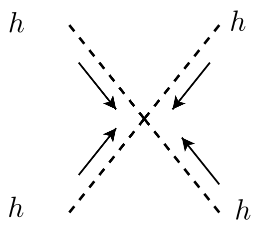
$$-\frac{i}{2}\,g^2\,\frac{m_h^2}{m_W^2} \tag{D.88}$$



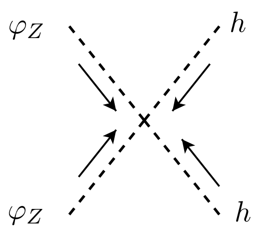
$$-\frac{i}{4}\,g^2\,\frac{m_h^2}{m_W^2} \tag{D.89}$$



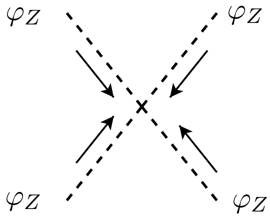
$$-\frac{i}{4}\,g^2\,\frac{m_h^2}{m_W^2} \tag{D.90}$$



$$-\frac{3}{4}\,i\,g^2\,\frac{m_h^2}{m_W^2} \tag{D.91}$$



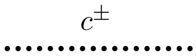
$$-\frac{i}{4}\,g^2\,\frac{m_h^2}{m_W^2} \tag{D.92}$$



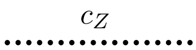
$$-\frac{3}{4}\, i\, g^2 \frac{m_h^2}{m_W^2} \tag{D.93}$$

D.4.11 Ghost Propagators

$$\frac{i}{k^2 + i\epsilon} \tag{D.94}$$

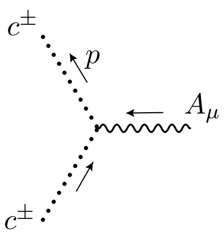


$$\frac{i}{k^2 - \xi m_W^2 + i\epsilon} \tag{D.95}$$

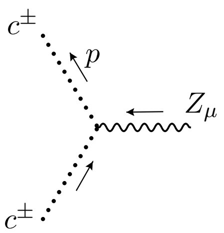


$$\frac{i}{k^2 - \xi m_Z^2 + i\epsilon} \tag{D.96}$$

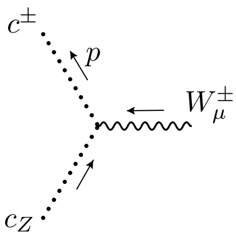
D.4.12 Ghost Gauge Interactions



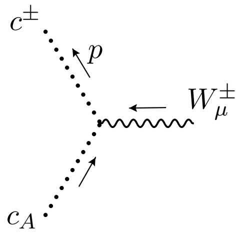
$$\mp ie\, p_\mu \tag{D.97}$$



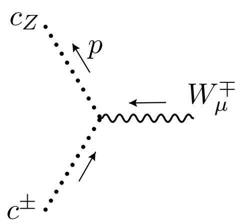
$$\pm ig\, \cos\theta_W\, p_\mu \tag{D.98}$$



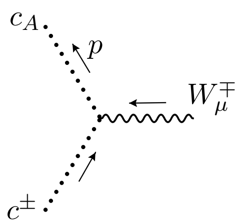
$$\mp\, ig\, \cos\theta_W\, p_\mu \tag{D.99}$$



$$\pm\, ie\, p_\mu \tag{D.100}$$

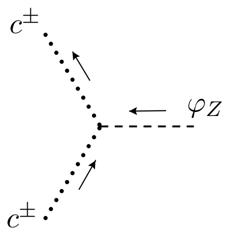


$$\mp\, ig\, \cos\theta_W\, p_\mu \tag{D.101}$$

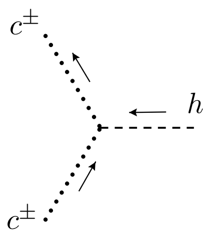


$$\pm\, ie\, p_\mu \tag{D.102}$$

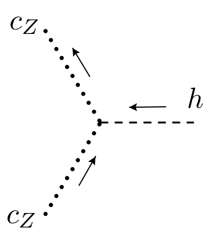
D.4.13 Ghost Higgs and Ghost Goldstone Interactions



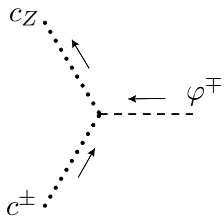
$$\pm\, \frac{g}{2}\, \xi\, m_W \tag{D.103}$$



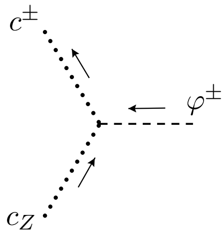
$$-\frac{i}{2}\, g\, \xi\, m_W \tag{D.104}$$



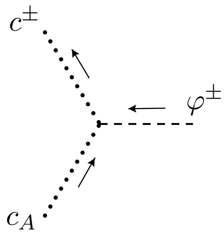
$$-\frac{ig}{2\cos\theta_W}\, \xi\, m_Z \tag{D.105}$$



$$\frac{i}{2}\, g\, \xi\, m_Z \tag{D.106}$$



$$-ig\, \frac{\cos 2\theta_W}{2\cos\theta_W}\, \xi\, m_W \tag{D.107}$$



$$ie\, \xi\, m_W \tag{D.108}$$