A.2 Feynman rules for the Electroweak Standard Model

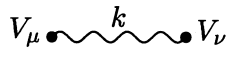
In this appendix we list the Feynman rules of the SM in an arbitrary 't Hooft gauge. We write down generic Feynman rules for all propagators and vertices and give the possible actual insertions. The rules for the external lines are as in (A.1.76) and (A.1.77). For brevity we introduce the shorthand notation

$$c = c_{\mathrm{w}} = \cos\theta_{\mathrm{w}}, \qquad s = s_{\mathrm{w}} = \sin\theta_{\mathrm{w}}. \tag{A.2.1}$$

In the vertices all momenta and fields are considered as incoming.

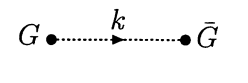
The propagators read as follows for

gauge bosons $V = A$, Z, and W ($M_A = 0$),



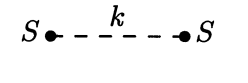
$$= \frac{-\mathrm{i}g_{\mu\nu}}{k^2 - M_V^2} + \frac{\mathrm{i}(1-\xi_V)k_\mu k_\nu}{(k^2 - M_V^2)(k^2 - \xi_V M_V^2)}, \tag{A.2.2}$$

Faddeev–Popov ghosts $G = u^A$, u^Z, and $u^\pm$ ($M_{u^A} = 0$, $M_{u^Z} = \sqrt{\xi_Z} M_{\mathrm{Z}}$, and $M_{u^\pm} = \sqrt{\xi_W} M_{\mathrm{W}}$),



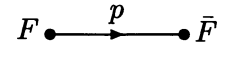
$$= \frac{\mathrm{i}}{k^2 - M_G^2}, \tag{A.2.3}$$

scalar fields $S = \eta$, χ, and ϕ ($M_\chi = \sqrt{\xi_Z} M_{\mathrm{Z}}$ and $M_\phi = \sqrt{\xi_W} M_{\mathrm{W}}$),



$$= \frac{\mathrm{i}}{k^2 - M_S^2}, \tag{A.2.4}$$

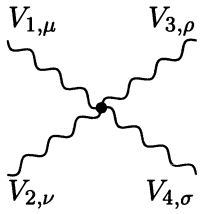
and fermion fields $F = f_i$,



$$= \frac{\mathrm{i}(\not{p} + m_F)}{p^2 - m_F^2}. \tag{A.2.5}$$

The vertices are given by the following expressions:

VVVV vertex:



$$= \mathrm{i}e^2 C\Big[2g_{\mu\nu}g_{\sigma\rho} - g_{\nu\rho}g_{\mu\sigma} - g_{\rho\mu}g_{\nu\sigma}\Big] \tag{A.2.6}$$

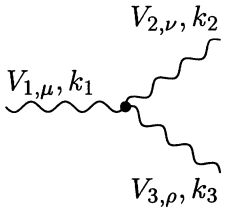
with the actual values of V_1, V_2, V_3, V_4, and C

$V_1V_2V_3V_4$	W^+W^-ZZ	W^+W^-AZ	W^+W^-AA
C	$-\frac{c^2}{s^2}$	$\frac{c}{s}$	-1

$V_1V_2V_3V_4$	$W^+W^+W^-W^-$
C	$\frac{1}{s^2}$

. (A.2.7)

VVV vertex:



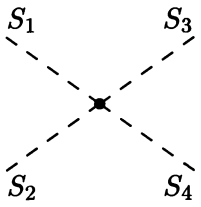
$$= \mathrm{i}eC\Big[g_{\mu\nu}(k_1 - k_2)_\rho + g_{\nu\rho}(k_2 - k_3)_\mu + g_{\rho\mu}(k_3 - k_1)_\nu\Big] \tag{A.2.8}$$

with the actual values of V_1, V_2, V_3, and C

$V_1V_2V_3$	AW^+W^-	ZW^+W^-
C	1	$-\frac{c}{s}$

. (A.2.9)

$SSSS$ vertex:



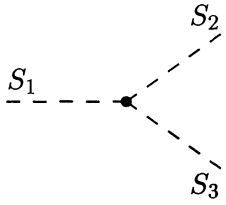
$$= \mathrm{i}e^2 C \tag{A.2.10}$$

with the actual values of S_1, S_2, S_3, S_4, and C

$S_1S_2S_3S_4$	$\eta\eta\eta\eta, \chi\chi\chi\chi$	$\eta\eta\chi\chi, \eta\eta\phi^+\phi^-, \chi\chi\phi^+\phi^-$	$\phi^+\phi^-\phi^+\phi^-$
C	$-\frac{3}{4s^2}\frac{M_\mathrm{H}^2}{M_\mathrm{W}^2}$	$-\frac{1}{4s^2}\frac{M_\mathrm{H}^2}{M_\mathrm{W}^2}$	$-\frac{1}{2s^2}\frac{M_\mathrm{H}^2}{M_\mathrm{W}^2}$

(A.2.11)

SSS vertex:



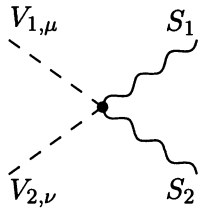
$$= \mathrm{i}eC \tag{A.2.12}$$

with the actual values of S_1, S_2, S_3, and C

$S_1S_2S_3$	$\eta\eta\eta$	$\eta\chi\chi, \eta\phi^+\phi^-$
C	$-\frac{3}{2s}\frac{M_\mathrm{H}^2}{M_\mathrm{W}}$	$-\frac{1}{2s}\frac{M_\mathrm{H}^2}{M_\mathrm{W}}$

(A.2.13)

$VVSS$ vertex:



$$= \mathrm{i}e^2 g_{\mu\nu} C \tag{A.2.14}$$

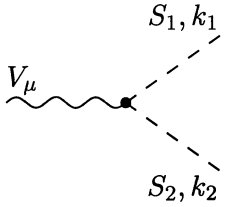
with the actual values of V_1, V_2, S_1, S_2, and C

$V_1V_2S_1S_2$	$ZZ\eta\eta$ $ZZ\chi\chi$	$W^+W^-\eta\eta$ $W^+W^-\chi\chi$ $W^+W^-\phi^+\phi^-$	$AA\phi^+\phi^-$	$ZA\phi^+\phi^-$	$ZZ\phi^+\phi^-$
C	$\frac{1}{2c^2s^2}$	$\frac{1}{2s^2}$	2	$-\frac{c^2-s^2}{cs}$	$\frac{(c^2-s^2)^2}{2c^2s^2}$

$V_1V_2S_1S_2$	$W^\pm A\phi^\mp\eta$	$W^\pm A\phi^\mp\chi$	$W^\pm Z\phi^\mp\eta$	$W^\pm Z\phi^\mp\chi$
C	$-\frac{1}{2s}$	$\mp\frac{\mathrm{i}}{2s}$	$-\frac{1}{2c}$	$\mp\frac{\mathrm{i}}{2c}$

. (A.2.15)

VSS vertex:



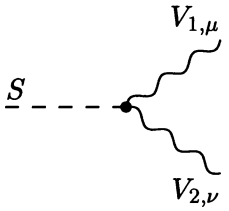
$$= \mathrm{i}eC(k_1 - k_2)_\mu \tag{A.2.16}$$

with the actual values of V, S_1, S_2, and C

VS_1S_2	$Z\chi\eta$	$A\phi^+\phi^-$	$Z\phi^+\phi^-$	$W^\pm\phi^\mp\eta$	$W^\pm\phi^\mp\chi$
C	$-\frac{\mathrm{i}}{2cs}$	-1	$\frac{c^2-s^2}{2cs}$	$\mp\frac{1}{2s}$	$-\frac{\mathrm{i}}{2s}$

. (A.2.17)

SVV vertex:



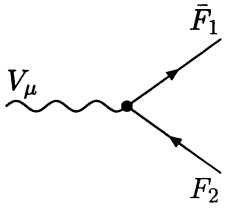
$$= \mathrm{i}e g_{\mu\nu} C \tag{A.2.18}$$

with the actual values of S, V_1, V_2, and C

SV_1V_2	ηZZ	ηW^+W^-	$\phi^\pm W^\mp A$	$\phi^\pm W^\mp Z$
C	$\frac{1}{c^2 s} M_\mathrm{W}$	$\frac{1}{s} M_\mathrm{W}$	$-M_\mathrm{W}$	$-\frac{s}{c} M_\mathrm{W}$

. (A.2.19)

$V\bar{F}F$ vertex:



$$= \mathrm{i}e\gamma_\mu \left(C_\mathrm{L} \frac{1-\gamma_5}{2} + C_\mathrm{R} \frac{1+\gamma_5}{2} \right) \tag{A.2.20}$$

with the actual values of V, $\bar{F}_1$, F_2, C_R, and C_L

$V\bar{F}_1F_2$	$A\bar{f}_i f_j$	$Z\bar{f}_i f_j$	$W^+\bar{u}_i d_j$	$W^-\bar{d}_j u_i$	$W^+\bar{\nu}_i l_j$	$W^-\bar{l}_j \nu_i$
C_L	$-Q_f \delta_{ij}$	$g_f^- \delta_{ij}$	$\frac{1}{\sqrt{2}s} V_{ij}$	$\frac{1}{\sqrt{2}s} V_{ji}^\dagger$	$\frac{1}{\sqrt{2}s} \delta_{ij}$	$\frac{1}{\sqrt{2}s} \delta_{ij}$
C_R	$-Q_f \delta_{ij}$	$g_f^+ \delta_{ij}$	0	0	0	0

, (A.2.21)

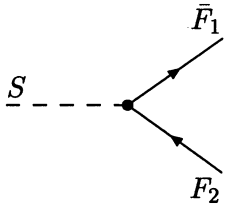
where

$$g_f^+ = -\frac{s}{c} Q_f, \qquad g_f^- = \frac{I_{\mathrm{w},f}^3 - s^2 Q_f}{sc}. \tag{A.2.22}$$

The *vector and axial-vector couplings* of the Z-boson are given by

$$\begin{aligned} v_f &= \frac{1}{2}(g_f^- + g_f^+) = \frac{I_{\mathrm{w},f}^3 - 2s^2 Q_f}{2sc}, \\ a_f &= \frac{1}{2}(g_f^- - g_f^+) = \frac{I_{\mathrm{w},f}^3}{2sc}. \end{aligned} \tag{A.2.23}$$

$S\bar{F}F$ vertex:



$$= \mathrm{i}e\left(C_{\mathrm{L}}\frac{1-\gamma_5}{2} + C_{\mathrm{R}}\frac{1+\gamma_5}{2}\right) \tag{A.2.24}$$

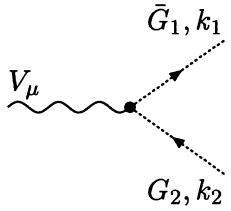
with the actual values of S, $\bar{F}_1$, F_2, C_{R}, and C_{L}

$S\bar{F}_1F_2$	$\eta\bar{f}_i f_j$	$\chi\bar{f}_i f_j$	$\phi^+\bar{u}_i d_j$	$\phi^-\bar{d}_j u_i$
C_{L}	$-\frac{1}{2s}\frac{m_{f,i}}{M_{\mathrm{W}}}\delta_{ij}$	$-\frac{\mathrm{i}}{2s}2I_{\mathrm{w},f}^3\frac{m_{f,i}}{M_{\mathrm{W}}}\delta_{ij}$	$+\frac{1}{\sqrt{2}s}\frac{m_{u,i}}{M_{\mathrm{W}}}V_{ij}$	$-\frac{1}{\sqrt{2}s}\frac{m_{d,j}}{M_{\mathrm{W}}}V_{ji}^\dagger$
C_{R}	$-\frac{1}{2s}\frac{m_{f,i}}{M_{\mathrm{W}}}\delta_{ij}$	$\frac{\mathrm{i}}{2s}2I_{\mathrm{w},f}^3\frac{m_{f,i}}{M_{\mathrm{W}}}\delta_{ij}$	$-\frac{1}{\sqrt{2}s}\frac{m_{d,j}}{M_{\mathrm{W}}}V_{ij}$	$+\frac{1}{\sqrt{2}s}\frac{m_{u,i}}{M_{\mathrm{W}}}V_{ji}^\dagger$

$S\bar{F}_1F_2$	$\phi^+\bar{\nu}_i l_j$	$\phi^-\bar{l}_j\nu_i$
C_{L}	0	$-\frac{1}{\sqrt{2}s}\frac{m_{l,j}}{M_{\mathrm{W}}}\delta_{ij}$
C_{R}	$-\frac{1}{\sqrt{2}s}\frac{m_{l,j}}{M_{\mathrm{W}}}\delta_{ij}$	0

. (A.2.25)

$V\bar{G}G$ vertex:



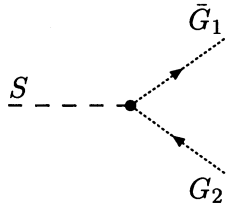
$$= \mathrm{i}ek_{1,\mu}C \tag{A.2.26}$$

with the actual values of V, $\bar{G}_1$, G_2, and C

$V\bar{G}_1G_2$	$A\bar{u}^{\pm}u^{\pm}, W^{\pm}\bar{u}^{A}u^{\mp}$ $W^{\mp}\bar{u}^{\mp}u^{A}$	$Z\bar{u}^{\pm}u^{\pm}, W^{\pm}\bar{u}^{Z}u^{\mp}$ $W^{\mp}\bar{u}^{\mp}u^{Z}$
C	± 1	$\mp\frac{c}{s}$

. (A.2.27)

$S\bar{G}G$ vertex:



$$= \mathrm{i}eC\xi_1 \tag{A.2.28}$$

with $\xi_1 = \xi_W, \xi_Z$ for $G_1 = u^{\pm}, u^Z$, respectively, and the actual values of S, $\bar{G}_1$, G_2, and C

$S\bar{G}_1G_2$	$H\bar{u}^{Z}u^{Z}$	$H\bar{u}^{\pm}u^{\pm}$	$\chi\bar{u}^{\pm}u^{\pm}$
C	$-\frac{1}{2c^2s}M_{\mathrm{W}}$	$-\frac{1}{2s}M_{\mathrm{W}}$	$\mp\frac{\mathrm{i}}{2s}M_{\mathrm{W}}$

$S\bar{G}_1G_2$	$\phi^{\pm}\bar{u}^{\pm}u^{A}$	$\phi^{\pm}\bar{u}^{\pm}u^{Z}$	$\phi^{\pm}\bar{u}^{Z}u^{\mp}$
C	M_{W}	$-\frac{c^2-s^2}{2cs}M_{\mathrm{W}}$	$\frac{1}{2cs}M_{\mathrm{W}}$

. (A.2.29)