Appendix B Feynman Rules of the Standard Model

B.1 Preliminaries

In this appendix we list all SM Feynman rules relevant for this book. These rules are simply derived by multiplying SM Lagrangian by i and reading off the interactions. We note that given the Feynman rule for a vertex obtained from one particular term in the Lagrangian, the rule for the conjugate vertex is obtained from the Hermitian conjugate of this particular term, subsequently multiplied by i. In this manner the elements of the CKM matrix V_{ij} and of PMNS matrix U_{ij} are replaced by V_{ij}^* and U_{ij}^*, respectively. Moreover, while the vector interactions like $V \pm A$ are unchanged by Hermitian conjugation, there is a chirality flip from $P_{L,R}$ to $P_{R,L}$ in the case of scalar interactions.

For anybody doing Feynman diagram calculations and comparing intermediate results with those given in the literature, a nightmare are various possible signs in the Feynman rules. A nice collection of various possibilities and comparison of them can be found in [1311]. The Feynman rules for QCD and electroweak interactions are given there in terms of various $\eta_i = \pm$ factors. Our rules correspond to

$$\eta_s = \eta = \eta_e = \eta' = -1, \qquad \eta_Z = \eta_Y = \eta_\theta = +1 \tag{B.1}$$

and are the same as in the book by Peskin and Schroeder [14]. We give all these factors here but for Feynman rules really only η_s, η, η_e, and η_Z are relevant. The remaining Feynman rules can be found in [1311].

Some vertices depend on the four-momenta of particles. All momenta in our rules are, as in [1311], *incoming.* A list of papers with Feynman rules in a number of extensions of the SM has been given in Section 16.1.

B.2 Gauge Boson Propagators

For gauge bosons we give them setting all gauge parameters to unity. General expressions can be found in [1311]. We have then ($a, b = 1, ..8$):

$$G_{\mu\nu}^{ab}(k) : -i\delta_{ab}\frac{g_{\mu\nu}}{k^2 + i\epsilon}, \qquad A_{\mu\nu}(k) : -i\frac{g_{\mu\nu}}{k^2 + i\epsilon}, \tag{B.2}$$

$$(W_{\mu\nu}^{\pm})(k) : -i\frac{g_{\mu\nu}}{k^2 - M_W^2 + i\epsilon}, \qquad Z_{\mu\nu}(k) : -i\frac{g_{\mu\nu}}{k^2 - M_Z^2 + i\epsilon}\,. \tag{B.3}$$

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B.3 Fermion and Scalar Propagators

For quarks q and leptons l the propagators read ($\alpha, \beta = 1, 2, 3$)

$$q(p)_{\alpha\beta} : i\delta_{\alpha\beta}\frac{\not{p} + m_q}{p^2 - m_q^2 + i\epsilon}, \qquad l(p) : i\frac{\not{p} + m_l}{p^2 - m_l^2 + i\epsilon}\,. \tag{B.4}$$

For pseudo-Goldstone bosons $G^{\pm,0}$ and Higgs H they are

$$G^{\pm}(p) : \frac{i}{p^2 - M_W^2 + i\epsilon}, \qquad G^0(p) : \frac{i}{p^2 - M_Z^2 + i\epsilon}\,, \tag{B.5}$$

$$H(p) : \frac{i}{p^2 - M_H^2 + i\epsilon}\,. \tag{B.6}$$

B.4 Fermion–Gauge Boson Couplings

$$\bar{q}_\alpha G^a_\mu q_\beta \; : \; ig_3\gamma_\mu t^a_{\alpha\beta}\,, \tag{B.7}$$

$$\bar{f}A_\mu f \; : \; ieQ_f\gamma_\mu\,, \tag{B.8}$$

$$\bar{u}_i Z_\mu u_i \; : \; \frac{ig_2}{\cos\vartheta_W}\gamma_\mu\left[\left(\frac{1}{2} - \frac{2}{3}\sin^2\vartheta_W\right)P_L - \frac{2}{3}\sin^2\vartheta_W P_R\right], \tag{B.9}$$

$$\bar{d}_i Z_\mu d_i \; : \; \frac{ig_2}{\cos\vartheta_W}\gamma_\mu\left[\left(-\frac{1}{2} + \frac{1}{3}\sin^2\vartheta_W\right)P_L + \frac{1}{3}\sin^2\vartheta_W P_R\right], \tag{B.10}$$

$$\bar{\nu}_i Z_\mu \nu_i \; : \; \frac{ig_2}{\cos\vartheta_W}\gamma_\mu\left[\frac{1}{2}P_L\right], \tag{B.11}$$

$$\bar{\ell}_i Z_\mu \ell_i \; : \; \frac{ig_2}{\cos\vartheta_W}\gamma_\mu\left[\left(-\frac{1}{2} + \sin^2\vartheta_W\right)P_L + \sin^2\vartheta_W P_R\right], \tag{B.12}$$

$$\bar{u}_i W^+_\mu d_j \; : \; \frac{ig_2}{\sqrt{2}}V_{ij}\gamma_\mu P_L\,, \qquad \bar{d}_j W^-_\mu u_i \; : \; \frac{ig_2}{\sqrt{2}}V^*_{ij}\gamma_\mu P_L\,, \tag{B.13}$$

$$\bar{\nu}_i W^+_\mu l_j \; : \; \frac{ig_2}{\sqrt{2}}U_{ij}\gamma_\mu P_L\,, \qquad \bar{l}_j W^-_\mu \nu_i \; : \; \frac{ig_2}{\sqrt{2}}U^*_{ij}\gamma_\mu P_L\,. \tag{B.14}$$

B.5 Fermion–Goldstone (Higgs) Boson Couplings

$$\bar{u}^i G^+ d^j \; : \; i\frac{g_2}{\sqrt{2}M_W}\left(m^i_u P_L - m^j_d P_R\right)V_{ij}, \tag{B.15}$$

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$$\bar{d}^j G^- u^i \,:\, i\frac{g_2}{\sqrt{2}M_W}\left(m_u^i P_R - m_d^j P_L\right) V_{ij}^*, \tag{B.16}$$

$$\bar{\nu}^i G^+ \ell^j \,:\, -i\frac{g_2}{\sqrt{2}}\frac{m_\ell^j}{M_W} P_R U_{ij}\,, \qquad \bar{\ell}^j G^- \nu^i \,:\, -i\frac{g_2}{\sqrt{2}}\frac{m_\ell^j}{M_W} P_L U_{ij}^*, \tag{B.17}$$

$$\bar{u}^i G^0 u^j \,:\, -\frac{g_2 m_u^i}{2M_W}\gamma_5\delta_{ij}\,, \qquad \bar{d}^i G^0 d^j \,:\, \frac{g_2 m_d^i}{2M_W}\gamma_5\delta_{ij}, \tag{B.18}$$

$$\bar{\ell}^i G^0 \ell^j \,:\, \frac{g_2 m_\ell^i}{2M_W}\gamma_5\delta_{ij}\,, \qquad \bar{f} H f = -i\frac{g}{2}\frac{m_f}{M_W}\,. \tag{B.19}$$

We have set $m_\nu^i = 0$ and $f = q, l$.

B.6 Gauge Boson Self-Interactions

$$G_\mu^a(p_1)G_\nu^b(p_2)G_\rho^c(p_3) \,:\, g_3 f^{abc}\left[g_{\mu\nu}(p_1-p_2)_\rho + g_{\nu\rho}(p_2-p_3)_\mu + g_{\rho\mu}(p_3-p_1)_\nu\right], \tag{B.20}$$

$$W_\sigma^-(p_-)W_\rho^+(p_+)Z_\mu(q) \,:\, ig_2\cos\vartheta_W\left[g_{\sigma\rho}(p_- - p_+)_\mu + g_{\rho\mu}(p_+ - q)_\sigma + g_{\mu\sigma}(q-p_-)_\rho\right], \tag{B.21}$$

$$W_\sigma^-(p_-)W_\rho^+(p_+)A_\mu(q) \,:\, ie\left[g_{\sigma\rho}(p_- - p_+)_\mu + g_{\rho\mu}(p_+ - q)_\sigma + g_{\mu\sigma}(q-p_-)_\rho\right]. \tag{B.22}$$

B.7 Gauge Boson–Goldstone (Higgs) Interactions

$$W_\mu^\pm Z_\nu G^\mp \,:\, -ig_2 M_W \frac{\sin^2\vartheta_W}{\cos\vartheta_W} g^{\mu\nu}\,, \qquad W_\mu^\pm A_\nu G^\mp \,:\, ieM_W g^{\mu\nu}, \tag{B.23}$$

$$G^+(p_+)G^-(p_-)Z_\mu \,:\, ig_2\frac{1-2\sin^2\vartheta_W}{2\cos\vartheta_W}(p_+-p_-)_\mu\,, \qquad G^+(p_+)G^-(p_-)A_\mu \,:\, ie(p_+-p_-)_\mu, \tag{B.24}$$

$$W_\mu^\pm H W_\nu^\mp \,:\, ig_2 M_W g_{\mu\nu}\,, \qquad Z_\mu H Z_\nu \,:\, i\frac{g_2}{\cos\vartheta_W} M_Z g^{\mu\nu}\,. \tag{B.25}$$

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