APPENDIX

DIMENSIONAL REGULARIZATION

Dimensional regularization [27] is widely used in calculations of radiative corrections. Since an analytic continuation in the space-time dimensions is not unique, there is a variety of conventions in this method. We adopt the following convention:

$$Tr(1) = 4 \tag{A.1}$$

$$\{\gamma_\mu, \gamma_5\} = 0 \tag{A.2}$$

and $\int \frac{d^n k}{(2\pi)^4}$ in n dimensional space. Below we list basic formulas in our convention.

The basic algebra is

$$\{\gamma_\mu, \gamma_5\} = 2g_{\mu\nu} \tag{A.3}$$

The metric tensor satisfies

$$g_{\mu\nu} g^{\mu\nu} = n. \tag{A.4}$$

Combining (A.1) and (A.2), we obtain

$$\gamma_\lambda \gamma^\lambda = n \tag{A.5}$$

$$\gamma_\lambda \gamma_\mu \gamma^\lambda = (2-n)\gamma_\mu \tag{A.6}$$

$$\gamma_\lambda \gamma_\mu \gamma_\nu \gamma^\lambda = 4g_{\mu\nu} + (n-4)\gamma_\mu \gamma_\nu \tag{A.7}$$

$$\gamma_\lambda \gamma_\mu \gamma_\nu \gamma_\rho \gamma^\lambda = -2\gamma_\rho \gamma_\nu \gamma_\mu + (4-n)\gamma_\mu \gamma_\nu \gamma_\rho. \tag{A.8}$$

Further, by using our convention on unit matrix 1,

$$Tr(1) = 4 \tag{A.9}$$

we find

$$Tr(\lambda_\mu \lambda_\nu) = 4g_{\mu\nu} \tag{A.10}$$

$$Tr(\lambda_\mu \lambda_\nu \lambda_\lambda \lambda_\rho) = 4(g_{\mu\nu}g_{\lambda\rho} + g_{\mu\rho}g_{\nu\lambda} - g_{\mu\lambda}g_{\nu\rho}) \tag{A.11}$$

As mentioned above, the γ_5 matrix is defined so that it satisfies Eq.(A.2). There occurs no trouble concerning the γ_5 matrix in the present case, since the Weinberg-Salam theory is an anomaly-free theory.

The Feynman parametrization is needed to combine a product of several different quadratic factors appearing in the denominators of the momentum integral. For an arbitrary number of factors, the Feynman parametrization is given by :

$$\frac{1}{a_1 a_2 \ldots\ldots a_n} = (n-1)! \int_0^1 U_1^{n-2} dU_1 \int_0^1 U_2^{n-3} dU_2 \ldots\ldots \int_0^1 dU_{n-1}$$

$$\times \left[(a_1 - a_2)U_1 \ldots U_{n-1} + (a_2 - a_3)U_1 \ldots U_{n-2} + \ldots + a_n\right]^{-n} \tag{A.12}$$

A special case of Eq.(A.11) used in our calculation is

$$\frac{1}{ab} = \int_0^1 dx[b + (a-b)x]^{-2} \tag{A.13}$$

After a Feynman parametrization of the propagators and a shift of the momentum variables, the momentum integrals reduce to an integral of the form:

$$I(m,r) = \int \frac{d^n \tilde{k}}{(2\pi)^n} \frac{(\tilde{k}^2)^r}{(\tilde{k}^2 - R^2)^m} \tag{A.14}$$

This Minkowsi space integral is performed after a Wick rotation into Euclidean space and we obtain the basic formula:

$$I(m,r)=\int\frac{d^n\tilde{k}}{(2\pi)^n}\frac{\left(\hat{k}^2\right)^r}{\left(\tilde{k}^2-R^2\right)^m}=\frac{i}{\left(16\pi^2\right)^{n/4}}(-1)^{r-m}\left(R^2\right)^{r-m+n/2}$$

$$\times\frac{\Gamma\left(r+n/2\right)\Gamma\left(m-r-n/2\right)}{\Gamma\left(n/2\right)\Gamma(m)} \tag{A.15}$$

By symmetrical integration, it can easily be proved that:

$$\int\frac{d^n\hat{k}}{(2\pi)^n}\frac{\tilde{k}_\mu\tilde{k}_\nu}{\left(\tilde{k}^2-R^2\right)^m}=\frac{1}{n}g_{\mu\nu}\int\frac{d^n\tilde{k}}{(2\pi)^n}\frac{\tilde{k}^2}{\left(\tilde{k}^2-R^2\right)^m} \tag{A.16}$$

and

$$\int\frac{d^n\tilde{k}}{(2\pi)^n}\frac{\tilde{k}_{\mu_1}\hat{k}_{\mu_2}....\tilde{k}_{\mu_q}}{\left(\tilde{k}^2-R^2\right)^m}=0 \qquad \text{for } q \text{ odd.} \tag{A.17}$$

The Gamma function $\Gamma(x)$ has the following properties:

$$\Gamma(\varepsilon)=1/\varepsilon-\gamma+O(\varepsilon) \tag{A.18}$$

$$\Gamma(\varepsilon-1)=-1/\varepsilon-(1-\gamma)+O(\varepsilon) \tag{A.19}$$

where $\gamma=0.5772$ is the Euler constant.