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INVESTIGATION OF SPONTANEOUSLY BROKEN GAUGE THEORIES

III. Three- and Four-Point Functions and Renormalization Constants

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Исследование спонтанно нарушенных калибровочных теорий.
III. Трех- и четырехточечные функции и постоянные перенормировки

Фермион-бозонные трехточечные функции общей СНКТ вычислены в однопетлевом приближении; они удовлетворяют соответствующим тождествам Уорда-Такахаши. Показано, что калибровочно инвариантные контрчлены, которые были введены раньше, делают теорию конечной. Ренормализационные константы и массовые контрчлены получены по методу 'т Хоофта.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1978

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Investigation of Spontaneously Broken Gauge Theories
III. Three- and Four-Point Functions and Renormalization Constants

The fermion-boson three-point functions of a general SBGT are calculated in one-loop approximation; they satisfy the corresponding WT identities. It is checked that the gauge invariant counterterms introduced earlier make the theory finite and the renormalization constants and mass counterterms are given by using 't Hooft's prescription.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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I. Introduction

In two previous papers (hereafter referred to as I and II[1]) we discussed the structure and the renormalization of general spontaneously broken gauge theories and gave the generating functional of the proper Green functions and two-point functions of the theory in one-loop approximation (II). In this Part we deal with the three- and four-point functions. The complete expression is given only for the fermion-boson vertices (Sec.II), and we discuss the implementation of the renormalization scheme we use in Sec. III where we list also the renormalization constants and mass counterterms determined from the pole terms of the appropriate proper Green functions.

II. The fermion-boson vertices

The general form of the three-point amplitudes is given by (9) of II. Below we write down the explicit expressions of the fermion-vector and fermion-scalar proper Green functions one gets after the momentum integration; the rather lengthy gauge dependent terms are omitted, thus the expressions are valid for $\xi = 0$ (Landau gauge). Similarly to the notations of II let us introduce the quantity

$$z_{abc}(pqk;st) = m_c^2 + s(m_b^2 - m_c^2 - q^2) + t(m_a^2 - m_b^2 + q^2 - k^2) + (sq + tp)^2 \tag{1}$$

where m_a, m_b, m_c may refer to any mass, p, q and k are external momenta. With an infrared cut-off Λ we write

$$D^k_{abc}(pqk;st) = z_{abc}(pqk;st)^{n/2-k}\,\Gamma(k - \tfrac{n}{2}) \tag{2.a}$$

$$E^{k(a)}_{abc} = \frac{1}{\Lambda^2 - m_a^2}\left(D^k_{\Lambda bc} - D^k_{abc}\right)$$

$$E^{k(b)}_{abc} = \frac{1}{\Lambda^2 - m_b^2}\left(D^k_{a\Lambda c} - D^k_{abc}\right) \tag{2.b}$$

$$E^{k(c)}_{abc} = \frac{1}{\Lambda^2 - m_c^2}\left(D^k_{ab\Lambda} - D^k_{abc}\right) \tag{2.c}$$

$$F^{k(a)}_{abc} = \frac{1}{(\Lambda^2 - m_b^2)(\Lambda^2 - m_c^2)}\left(D^k_{a\Lambda\Lambda} - D^k_{a\Lambda c} - D^k_{ab\Lambda} + D^k_{abc}\right) \tag{2.d}$$

$$F^{k(b)}_{abc} = \frac{1}{(\Lambda^2 - m_c^2)(\Lambda^2 - m_a^2)}\left(D^k_{\Lambda b\Lambda} - D^k_{ab\Lambda} - D^k_{\Lambda bc} + D^k_{abc}\right) \tag{2.e}$$

$$F^{k(c)}_{abc} = \frac{1}{(\Lambda^2 - m_a^2)(\Lambda^2 - m_b^2)}\left(D^k_{\Lambda\Lambda c} - D^k_{\Lambda bc} - D^k_{a\Lambda c} + D^k_{abc}\right). \tag{2.f}$$

(2.g)

In (2,b-g) the arguments are the same as in (2.a). For other notations we refer to II. We remark only that $\hat{t}_\alpha$ denotes the fermion-vector coupling in the representation where the fermion mass matrix m has the diagonal form $\hat{m} = \bar{\omega}^+ m\, \omega^+$, while for all momenta $\hat{p} = \gamma^\mu p_\mu$. P_a, Π_a and π_a are projections to the vector, scalar and fermion fields, respectively, with a given mass m_a.

With these notations the expressions for the fermion - vector proper Green functions (counterterms + one-loop corrections) are:

$$\Gamma^\mu_\alpha(pqk) = [\delta_{\alpha\beta} Z_2 + (Z_1 - Z_3)_{\alpha\beta}]\gamma^\mu t_\beta + \frac{\pi^{n/2}}{2(2\pi)^n}\int_0^1 ds \int_0^s dt\, \bar{\omega}\left(\Gamma^\mu_{1\alpha}(pqk;st) + \Gamma^\mu_{2\alpha}(pqk;st)\right)\omega, \tag{3}$$

where Γ_1 and Γ_2 are the contributions of the diagrams (1) and (2), respectively, in Fig.1.

Fig.1.

$$\begin{aligned}
\Gamma^\mu_{1\alpha}(pqk;st) = {} & 2D^3_{abc}(pqk;st)\{\bar{\hat{t}}_b \pi_a [(n-2)(\hat{m}+\hat{u})\hat{t}_\alpha \gamma^\mu(\hat{m}+\hat{x}) + \\
& + 2(\hat{m}+\hat{u})\hat{x}\gamma^\mu \hat{t}_\alpha + 2\gamma^\mu \hat{t}_\alpha(\hat{m}-\hat{x})\hat{u} - \hat{y}(\hat{m}-\hat{u})\gamma^\mu \hat{t}_\alpha \\
& - \gamma^\mu \hat{t}_\alpha(\hat{m}-\hat{q})\hat{y}]\pi_c \hat{t}_b + \\
& + \hat{\Gamma}_b \pi_a(\hat{m}-\hat{u})\gamma^\mu t_\alpha \pi_c \hat{\Gamma}_b\} + \\
& + D^2_{abc}(pqk;st)\{(n-1)(n-4)\bar{\hat{t}}_b \pi_a \gamma^\mu \hat{t}_\alpha \pi_c \hat{t}_b + \\
& + (n-2)\hat{\Gamma}_b \pi_a \hat{t}_\alpha \gamma^\mu \pi_c \hat{\Gamma}_b\} + \\
& + 2E^{3(b)}_{abc}(pqk;st)\bar{\hat{t}}_b \pi_a \hat{y}(\hat{m}+\hat{p})\gamma^\mu \hat{t}_\alpha(\hat{m}-\hat{q})\hat{y}\pi_c \hat{t}_b + \\
& + 2E^{2(b)}_{abc}(pqk;st)\hat{t}_b \pi_a[(n-2)(\hat{m}-\hat{p})\hat{t}_\alpha \gamma^\mu(\hat{m}+\hat{q}) - \\
& - 2\gamma^\mu \hat{t}_\alpha \pi_a(\hat{m}-\hat{q})\hat{p} + \\
& + 2(\hat{m}-\hat{p})\hat{q}\gamma^\mu \hat{t}_\alpha]\pi_c \hat{t}_b,
\end{aligned}$$

$$
\begin{aligned}
\Gamma^{\mu}_{2\,\alpha}(pqk;st) = {} & \hat{f}_{\beta}\,\pi_b \{ 4 D^3_{abc}(pqk;st) [\gamma^{\mu}(\hat{m}+\hat{y})\hat{k} - \\
& - \hat{k}(\hat{m}+\hat{y})\gamma^{\mu} + k^2\gamma^{\mu} - k^{\mu}\hat{k} + \tfrac{1}{2}(u+x)^{\mu}(\hat{q}-\hat{p}+ \\
& + (n-1)(\hat{y}-\hat{m}))] - \\
& - 2(n-1) D^2_{abc}(pqk;st)\gamma^{\mu} + \\
& + 4 E^{3(a)}_{abc}(pqk;st)[ku\,\hat{u}(\hat{m}+\hat{p})\gamma^{\mu} - k^{\mu} pu\,\hat{u} - \\
& - \tfrac{1}{4}(x+u)^{\mu}\hat{u}\,(\tfrac{k^2}{2} - 2pu + (\hat{m}+\hat{p})\hat{k})] +
\end{aligned}
\tag{3.a}
$$

$$
\begin{aligned}
& + 4 E^{3(c)}_{abc}(pqk;st)[kx\,\gamma^{\mu}(\hat{q}-\hat{m})\hat{x} - k^{\mu} qx\,\hat{x} - \\
& \quad - \tfrac{1}{4}(x+u)^{\mu}(\tfrac{k^2}{2} + 2qx + \hat{k}(\hat{q}-\hat{m}))\hat{x}] - \\
& - E^{2(a)}_{abc}(pqk;st)[3\hat{k}(\hat{m}+\hat{p})\gamma^{\mu} + \hat{x}(\hat{m}+\hat{p})\gamma^{\mu} + \\
& \quad + \gamma^{\mu}(\hat{m}+\hat{p})\hat{x} + 2x^{\mu}(2\hat{p}-\hat{m}) + k^{\mu}(\hat{p}-2\hat{m}) - \tfrac{k^2}{2}\gamma^{\mu}] + \\
& + E^{2(c)}_{abc}(pqk;st)[3\gamma^{\mu}(\hat{m}-\hat{q})\hat{k} + \gamma^{\mu}(\hat{q}-\hat{m})\hat{u} + \\
& \quad + \hat{u}(\hat{q}-\hat{m})\gamma^{\mu} + 2u^{\mu}(2\hat{q}+\hat{m}) - k^{\mu}(\hat{q}+2\hat{m}) + \tfrac{k^2}{2}\gamma^{\mu}] + \\
& + \tfrac{k^2}{2} F^{3(b)}_{abc}(pqk;st)(u+x)^{\mu}\,\hat{u}(\hat{q}-\hat{p}-2\hat{m})\hat{x} + \\
& + \tfrac{k^2}{2} F^{2(b)}_{abc}(pqk;st)[\gamma^{\mu}(2\hat{m}-\hat{q}+\hat{p})\hat{x} + \hat{u}(2\hat{m}-\hat{q}+\hat{p})\gamma^{\mu} + \\
& \quad + (x+u)^{\mu}(n\hat{m} + \tfrac{n-2}{2}(\hat{q}-\hat{p}))]\}\hat{f}_{\gamma}(P_c T_{\alpha} P_a)_{\gamma\beta} + \\
& + \bar{\hat{f}}_{\beta}\,\pi_b\{2 D^3_{abc}(pqk;st)[u^{\mu} - \gamma^{\mu}(\hat{y}+\hat{m})] + \\
& \quad + 2 E^{3(a)}_{abc}(pqk;st)\,u^{\mu}\hat{u}(\hat{m}+\hat{p}) - \\
& \quad - E^{2(a)}_{abc}(pqk;st)\gamma^{\mu}(\hat{m}+\hat{p})\}\hat{\Gamma}_i(\Pi_c\bar{B}_{\alpha}P_a)_{i\beta} + \\
& + \hat{\Gamma}_i\,\pi_b\{2 D^3_{abc}(pqk;st)[(\hat{y}+\hat{m})\gamma^{\mu} - x^{\mu}] + \\
& \quad + 2 E^{3(c)}_{abc}(pqk;st)\,x^{\mu}(\hat{q}-\hat{m})\hat{x} + \\
& \quad + E^{2(c)}_{abc}(pqk;st)(\hat{m}-\hat{q})\gamma^{\mu}\}\hat{f}_{\beta}(P_c B_{\alpha}\Pi_a)_{\beta i} + \\
& + \hat{\Gamma}_i\,\pi_b\{2 D^3_{abc}(pqk;st)(u+x)^{\mu}(\hat{y}+\hat{m}) - \\
& \quad - 2 D^2_{abc}(pqk;st)\gamma^{\mu}\}\hat{\Gamma}_j(\Pi_c\vartheta_{\alpha}\Pi_a)_{ji}\,.
\end{aligned}
\tag{3.b}
$$

Here x, y and u are the following combinations of the external momenta:

$$
x = sq + tp\,, \quad y = x - q\,, \quad u = x + k\,. \tag{4}
$$

For the fermion-scalar vertex we have:

$$
\begin{aligned}
\Gamma_i(pqk) = -\Gamma_i^{0} + \frac{\pi^{n/2}}{2(2\pi)^n}\int_0^1 ds\int_0^1 dt\,\bar{\omega}\,(& \Gamma_{1i}(pqk;st) + \\
& + \Gamma_{2i}(pqk;st))\,\omega\,,
\end{aligned}
\tag{5}
$$

where Γ_1 and Γ_2 are again the contributions of the corresponding diagrams in Fig. 1 and are given by the expressions

$$
\begin{aligned}
\Gamma_{1i}(pqk;st) = {} & 2 D^3_{abc}(pqk;st)\{\bar{\hat{f}}_b\,\pi_a[n(\hat{m}+\hat{u})\hat{\Gamma}^{+}_i(\hat{m}+\hat{x} - \\
& - 2(\hat{m}+\hat{u})\hat{x}\hat{\Gamma}_i - 2\hat{\Gamma}_i(\hat{m}-\hat{x})\hat{u} + \hat{y}(\hat{m}-\hat{u})\hat{\Gamma}_i + \\
& + \hat{\Gamma}_i(\hat{m}-\hat{q})\hat{y}]\,\pi_c\hat{f}_b - \\
& - \hat{\Gamma}_b\,\pi_a(\hat{m}-\hat{u})\hat{\Gamma}_i(\hat{m}-\hat{x})\pi_c\hat{\Gamma}_b\} + \\
& + D^2_{abc}(pqk;st)\{n\hat{\Gamma}_b\,\pi_a\hat{\Gamma}^{+}_i\hat{\Gamma}_b - \\
& - n(n-1)\bar{\hat{f}}_b\,\pi_a\hat{\Gamma}_i\,\pi_c\hat{f}_b\} \\
& - 2 E^{(3,b)}_{abc}(pqk;st)\{\bar{\hat{f}}_b\,\pi_a\hat{y}(\hat{m}+\hat{p})\hat{\Gamma}_i\,\cdot \\
& \qquad \cdot(\hat{m}-\hat{q})\hat{y}\,\pi_c\hat{f}_b\} + \\
& + E^{2(b)}_{abc}(pqk;st)\bar{\hat{f}}_b\,\pi_a\{n(\hat{m}-\hat{p})\hat{\Gamma}^{+}_i(\hat{m}+\hat{q}) + \\
& \quad + 2[(\hat{p}-\hat{m})\hat{q}\hat{\Gamma}_i + \hat{\Gamma}_i(\hat{m}-\hat{q})\hat{p}]\}\pi_c\hat{f}_b
\end{aligned}
$$

$$
\begin{aligned}
\Gamma_{2i}(pqk;st) = {} & \bar{\hat{f}}_{\alpha}\,\pi_b\{2 D^3_{abc}(pqk;st)[\hat{q}-\hat{p}+(n-1)(\hat{y}-\hat{m})] \\
& + E^{3(a)}_{abc}(pqk;st)\,\hat{u}[\tfrac{k^2}{2} + 2pu + (\hat{m}+\hat{p})\hat{k}] + \\
& + E^{3(c)}_{abc}(pqk;st)[\tfrac{k^2}{2} - 2qx + \hat{k}(\hat{q}-\hat{m})]\hat{x} + \\
& + E^{2(c)}_{abc}(pqk;st)\hat{q} - E^{2(a)}_{abc}(pqk;st)\hat{p} + \\
& + \tfrac{k^2}{2} F^{3(b)}_{abc}(pqk;st)\,\hat{u}(2\hat{m}+\hat{p}-\hat{q})\hat{x} -
\end{aligned}
\tag{5.a}
$$

$$-\frac{k^2}{2} F^{2(b)}_{abc}(pqk;st)\left[n\hat{m} + \frac{n-2}{2}(\hat{q}-\hat{p})\right]\Big\} f_\beta (P_c\beta; P_a)_{\beta\alpha}$$
$$+\bar{\hat{f}}_\alpha \pi_b \Big\{ 4D^3_{abc}(pqk;st)\left[ku - \hat{k}(\hat{m}+\hat{y})\right] +$$
$$+ 4E^{3(a)}_{abc}(pqk;st)\, ku\, \hat{u}\, (\hat{m}+\hat{p}) -$$
$$- 2E^{2(a)}_{abc}(pqk;st)\, \hat{k}\, (\hat{p}+\hat{m}) \Big\} \hat{r}_j (\Pi_c\delta; P_a)_{j\alpha} +$$
$$+ \hat{r}_j \pi_b \Big\{ 4D^3_{abc}(pqk;st)\left[(\hat{m}+\hat{y})\hat{k} - kx\right] +$$
$$+ 4E^{3(c)}_{abc}(pqk;st)\, kx\, (\hat{q}-\hat{m})\hat{x} +$$
$$+ 2E^{2(c)}_{abc}(pqk;st)\, (\hat{m}-\hat{q})\hat{k} \Big\} \hat{t}_\alpha (P_c\delta; \Pi_a)_{\alpha j} \quad (5.b)$$
$$+ \hat{r}_j \pi_b\, 2D^3_{abc}(pqk;st)(\hat{y}+\hat{m})\hat{r}_k (\Pi_c\gamma; \Pi_a)_{kj}.$$

In order to check our calculations we have satisfied ourselves that the expressions (3) and (5) satisfy the identities (37,a) of I, written for the spontaneously broken case and for the renormalized functions:

$$I_{\alpha\alpha'}(k^2)\, k_\mu \Gamma^{a\,\mu}_{b\,\alpha'}(pqk) + Z_{i\alpha}(k^2)\Gamma^a_{bi}(pqk) =$$
$$= \Gamma^a_c(p)\,\Sigma^c{}_{\alpha b}(pqk) + \Sigma_{c\alpha}{}^a(qkp)\,\Gamma^c_b(-q), \quad (6)$$

where

$$Z_{i\alpha}(k^2) = I_{\alpha\alpha'}(k^2)\, C_{\alpha' j}(k^2)\, \Gamma^{-1}_{ji}(k^2),$$

$I_{\alpha\beta}$, Γ^a_b, Γ_{ij} and $C_{\alpha j}$ are the corresponding proper two-point functions of the theory, and $\Sigma^a{}_{\alpha b}$ is defined by the equation

$$t_\beta{}^a{}_b\, Z_{1\,\beta\gamma}'\, Z_{\gamma\alpha}{}^a{}_b = \Sigma^a{}_{\alpha' c}\, G_{\alpha'\alpha}\, C^c_b$$

(cf. Equ's (34) and (47) in I) with Z_1' the ghost vertex renormalization constant and $Z_{\alpha\beta}{}^a{}_b$ the ghost-fermion four-point function. For the one-loop approximation $Z_{\alpha\beta}{}^a{}_b$ can be taken from the diagrams of Fig.2.

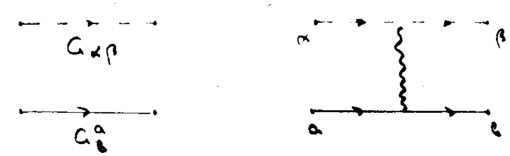

Fig.2.

We note that for off-mass-shell external momenta there are no infrared divergencies and we can satisfy (6) by dropping all terms proportional to the IR cut-off Λ.

In a later publication we shall use Γ^μ_α to calculate the general weak correction to the $g-2$ factor of the muon. Here we state only that our results are in agreement with the values obtained in special spontaneously broken gauge theory models (/2,3/ cf. also /4,5/).

III. Renormalization constants and mass counterterms

In this section we briefly discuss the choice of the counter terms and the realization of the renormalization procedure described in I. A very simple prescription for the counterterms has been proposed by 't Hooft /6/: one chooses them so as to just kill the pole terms in the dimensionally regularized Green functions. This method has the advantage that the renormalization constants are mass independent and the treatment of the renormalization group equations becomes much simpler (/6/; see also /7/).

From (9) and (10) of II one can easily determine the pole terms also for the Green functions we have not discussed so far and convince oneself that the counterterms written down in the Appendix of I will indeed eliminate all divergencies. We want to comment only one point here: the choice of the mass counterterm $\delta\mu^2$ and that of $\delta\lambda$, the finite change in the scalar vacuum expectation value. According to I they have to be adjusted so as to make to vanish either $\Gamma_i^{(1)}$ or the transversal part of the inverse scalar propagator at $p=0$. After taking into account all vertex counterterms the $\delta\mu^2$, given below, makes finite both $\Gamma_i^{(1)}$ and Γ_{ij}. This $\delta\mu^2$ is G-symmetric and independent of λ and ξ. Then we are left with a finite $\Gamma_i^{(1)}$;

$$\Gamma_i^{fin} = -(\mu^2\delta\lambda)_i + S_i\,, \tag{7}$$

$$\begin{aligned} S_i = \frac{1}{32\pi^2}\mathrm{Tr}\{ & M^2\{\vartheta_i\vartheta_k\}\lambda_k - \mu^2\gamma_i - 2\hat{m}^3\hat{\Gamma}_i - \\ & - m_a^2 \ln m_a^2\,(3P_a\{\vartheta_i\vartheta_k\}\lambda_k - \Pi_a\gamma_i - \\ & - 2\pi_a\hat{m}\hat{\Gamma}_i) + \ln\Lambda^2\,\xi\,\varrho\,\gamma_i\,\bar{\varrho}\,\}. \end{aligned} \tag{8}$$

From here we get

$$\delta\lambda_i = \mu^{-2}_{ij} S_j$$

and it is easy to show that with this $\delta\lambda$

$$\Gamma_{ij}(p=0)\,\vartheta_{\alpha,jk}(\lambda_k + \delta\lambda_k) = 0.$$

Since

$$\begin{aligned} \mathrm{Tr}\{M^2\{\vartheta_i\vartheta_k\}\lambda_k - \mu^2\gamma_i - 2\hat{m}^3\hat{\Gamma}_i + \ln\Lambda^2\,\xi\,\varrho\,\gamma_i\,\bar{\varrho}\,\} = \\ = \frac{1}{2}\frac{\partial}{\partial\lambda_i}\mathrm{Tr}[M^4 + \mu^4 - \hat{m}^4 - 2\ln\Lambda^2\,\xi\,\varrho\,\mu^2\,\bar{\varrho}\,] \end{aligned}$$

and the trace on the right-hand side is a fourth order invariant polynomial in λ (cf.[8]), this part of S_i gives a contribution to τ in (I.16) which can be taken into account by finite renormalizations of the couplings of the scalar self interaction $P(\varphi)$; the IR term disappears in the Landau gauge.

Below we give the list of the renormalization constants and mass counterterms obtained by using the prescription of [6] and which can be used for the renormalization group equations as described in [6,7]. (Note that for the fermion operators the Dirac trace is not separated in these expressions).

$$\begin{aligned}
Z_{3,\alpha\beta} &= \delta_{\alpha\beta} - \frac{1}{16\pi^2(n-4)}\mathrm{Tr}\left[\left(\frac{13}{3}-\xi\right)T_\alpha T_\beta - \frac{1}{3}\vartheta_\alpha\vartheta_\beta - \frac{2}{3}t_\alpha t_\beta\right] \\
Z_{1,\alpha\beta} &= \delta_{\alpha\beta} - \frac{1}{16\pi^2(n-4)}\mathrm{Tr}\left[\left(\frac{17}{6}-\frac{3}{2}\xi\right)T_\alpha T_\beta - \frac{1}{3}\vartheta_\alpha\vartheta_\beta - \frac{2}{3}t_\alpha t_\beta\right] \\
Z_2 &= 1 + \frac{1}{16\pi^2(n-4)}\left(\Gamma_i\Gamma_i^+ + 2\,\xi_{\alpha\beta}\,\bar{t}_\beta\bar{t}_\alpha\right) \\
Z_{ij} &= \delta_{ij} + \frac{1}{16\pi^2(n-4)}\mathrm{Tr}\left[(2\xi-6)\vartheta_i\vartheta_j + \Gamma_i\Gamma_j^+\right] \\
\Gamma_i' &= \Gamma_i - \frac{1}{16\pi^2(n-4)}\left[2\Gamma_k\Gamma_i^+\Gamma_k - 6\bar{t}_\alpha\Gamma_i t_\alpha - \mathrm{Tr}(\xi\vartheta_i\vartheta_l)\Gamma_l - \right. \\
&\qquad \left. - \xi_{\alpha\beta}(\Gamma_i t_\alpha t_\beta + \bar{t}_\alpha\bar{t}_\beta\Gamma_i)\right] \\
c'_{ijk} &= c_{ijk} - \frac{1}{16\pi^2(n-4)}\mathrm{Tr}\sum_{\substack{\text{perm}\\ i,j,k}}\left[\frac{1}{2}c_i f_{jk} - 2m_0\Gamma_i^+\Gamma_j\Gamma_k^+ - \xi\vartheta_i c_j\vartheta_k\right] \\
f'_{ijkl} &= f_{ijkl} - \frac{1}{16\pi^2(n-4)}\mathrm{Tr}\sum_{\substack{\text{perm}\\ i,j,k,l}}\left[\frac{1}{8}\left(f_{ij}f_{kl} + 3\{\vartheta_i\vartheta_j\}\{\vartheta_k\vartheta_l\}\right) - \right. \\
&\qquad \left. - \frac{1}{2}\Gamma_i\Gamma_j^+\Gamma_k\Gamma_l^+ - \frac{1}{2}\vartheta_i\,\xi\,\vartheta_j f_{kl}\right] \\
\\
\delta\mu^2_{ij} &= -\frac{1}{16\pi^2(n-4)}\mathrm{Tr}\left[6\vartheta_i\vartheta_j\mu^2 - f_{ij}\mu^2 - c_i c_j + 2m_0^+ m_0 \times \right. \\
&\qquad \times(\Gamma_i^+\Gamma_j + \Gamma_j^+\Gamma_i) + 2m_0\Gamma_i^+ m_0\Gamma_j^+ - \\
&\qquad \left. - \frac{1}{2}(\mu_0^2{}_{ik}\Gamma_k\Gamma_j^+ + \Gamma_i\Gamma_k^+\mu_0^2{}_{kj})\right] \\
\delta m &= -\frac{1}{16\pi^2(n-4)}\left[6\bar{t}_\alpha m_0 t_\alpha - 2\Gamma_i m_0^+\Gamma_i - \frac{1}{2}(m_0\Gamma_i^+\Gamma_i + \Gamma_i\Gamma_i^+ m_0)\right] \\
Z'_{3,\alpha\beta} &= \delta_{\alpha\beta} - \frac{1}{16\pi^2(n-4)}\mathrm{Tr}\left[3/2 - 1/2\,\xi\right]T_\alpha T_\beta
\end{aligned} \tag{9}$$

As it can be seen, the mass counterterms are independent of the gauge parameter ξ.

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