

Carlo M. Becchi and Giovanni Ridolfi

**An introduction to relativistic processes and the standard model
of electroweak interactions**

Errata

1. Page 5, line 9: replace “it absolute minimum” by “its absolute minimum”
2. Page 7, eq. (2.31): replace the last line by

$$= \partial_\mu \left[\sum_{i,j=1}^2 \epsilon_{ij} \phi_j(x) \frac{\partial \mathcal{L}(x)}{\partial \partial_\mu \phi_i(x)} \right] = 0,$$

3. Page 9: replace eq. (2.41) by

$$E = \frac{1}{2c^2} \sum_{\mathbf{k}} \left[|\partial_t \tilde{\phi}_{\mathbf{k}}|^2 + \omega_{\mathbf{k}}^2 |\tilde{\phi}_{\mathbf{k}}|^2 \right],$$

4. Page 9: replace eq. (2.42) by

$$\frac{\omega_{\mathbf{k}}^2}{c^2} = |\mathbf{k}|^2 + \mu^2.$$

5. Page 9: replace eq. (2.43) by

$$\tilde{\phi}_{\mathbf{k}} = c \sqrt{\frac{\hbar}{2\omega_{\mathbf{k}}}} (A_{\mathbf{k}} + A_{-\mathbf{k}}^\dagger), \quad \partial_t \tilde{\phi}_{\mathbf{k}} = -ic \sqrt{\frac{\hbar\omega_{\mathbf{k}}}{2}} (A_{\mathbf{k}} - A_{-\mathbf{k}}^\dagger).$$

6. Page 9: replace eq. (2.48) by

$$\hbar\omega_{\mathbf{k}} = \sqrt{c^2 \hbar^2 (\mathbf{k}^2 + \mu^2)}$$

7. Page 10: replace eqs. (2.50-51) by

$$\begin{aligned} A_{\mathbf{k}} |\{N_{\mathbf{q}}\}\rangle &= \sqrt{N_{\mathbf{k}}} |\{N_{\mathbf{q}} - \delta_{\mathbf{k},\mathbf{q}}\}\rangle \\ A_{\mathbf{k}}^\dagger |\{N_{\mathbf{q}}\}\rangle &= \sqrt{N_{\mathbf{k}} + 1} |\{N_{\mathbf{q}} + \delta_{\mathbf{k},\mathbf{q}}\}\rangle. \end{aligned}$$

8. Page 10: replace eq. (2.58) by

$$\mathbf{k} \cdot \mathbf{x} = \omega_{\mathbf{k}} t - \mathbf{k} \cdot \mathbf{r},$$

9. Page 15: replace eq. (3.13) by

$$\int d\mathbf{q} \mathcal{S}_{\mathbf{k},\mathbf{q}} \mathcal{S}_{\mathbf{p},\mathbf{q}}^* = \delta(\mathbf{k} - \mathbf{p}).$$

10. Page 15: replace eq. (3.14) by

$$\delta(E_k - E_p)[\mathcal{F}_{\mathbf{k},\mathbf{p}} - \mathcal{F}_{\mathbf{p},\mathbf{k}}^*] = -2\pi i \delta(E_k - E_p) \int d\mathbf{q} \delta(E_k - E_q) \mathcal{F}_{\mathbf{k},\mathbf{q}} \mathcal{F}_{\mathbf{p},\mathbf{q}}^*$$

11. Page 18, eq. (3.30): replace the last line by

$$\delta(\mathbf{q}_1 + \mathbf{q}_2 - \mathbf{q}'_1 - \mathbf{q}'_2) \delta(\mathbf{v}_1 \cdot (\mathbf{q}_1 - \mathbf{q}'_1) + \mathbf{v}_2 \cdot (\mathbf{q}_2 - \mathbf{q}'_2)).$$

12. Page 23: replace eq. (3.61) by

$$\phi^{(\text{as})}(\mathbf{x}, t) = \frac{1}{\sqrt{(2\pi)^3}} \int \frac{d\mathbf{k}}{\sqrt{2E_k}} \left[\sum_{i=1}^2 \psi_{\mathbf{p}_i}(\mathbf{k}) e^{-i\mathbf{k}\cdot\mathbf{x}} + \sum_{j=1}^n \psi_{\mathbf{k}_j}^*(-\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x}} \right].$$

13. Page 24: replace eq. (3.72) by

$$\begin{aligned} \phi(\mathbf{r}, t) &= \phi^{(\text{as})}(\mathbf{r}, t) + \int dt' \int d\mathbf{k} e^{i\mathbf{k}\cdot\mathbf{r}} \tilde{\Delta}(\mathbf{k}, t - t') \frac{1}{(2\pi)^3} \int d\mathbf{r}' e^{-i\mathbf{k}\cdot\mathbf{r}'} J(\mathbf{r}', t') \\ &= \phi^{(\text{as})}(x) + \int d^4x' J(x') \frac{1}{(2\pi)^3} \int d\mathbf{k} e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')} \tilde{\Delta}(\mathbf{k}, t - t'), \end{aligned}$$

14. Page 25: replace eq. (3.74), the following sentence, and eq. (3.75) by

$$\begin{aligned} &\frac{1}{(2\pi)^3} \int d\mathbf{k} e^{i\mathbf{k}\cdot\mathbf{r}} \tilde{\Delta}(\mathbf{k}, t) \\ &= - \int \frac{d\mathbf{k}}{(2\pi)^4} e^{i\mathbf{k}\cdot\mathbf{r}} \frac{1}{2E_k} \int_{-\infty}^{+\infty} d\omega \left[\frac{e^{-i(E_k+\omega)t}}{\omega + i\epsilon} + \frac{e^{i(E_k+\omega)t}}{\omega + i\epsilon} \right] \\ &= \int \frac{d^4k}{(2\pi)^4} e^{-i\mathbf{k}\cdot\mathbf{x}} \frac{1}{2E_k} \left[\frac{1}{E_k - k^0 - i\epsilon} + \frac{1}{E_k + k^0 - i\epsilon} \right], \end{aligned}$$

where we have defined $k^0 = E_k + \omega$ in the first term, $k^0 = -E_k - \omega$ in the second one, and $k = (k^0, \mathbf{k})$. This gives

$$\frac{1}{(2\pi)^3} \int d\mathbf{k} e^{i\mathbf{k}\cdot\mathbf{r}} \tilde{\Delta}(\mathbf{k}, t) = \frac{1}{(2\pi)^4} \int d^4k e^{-i\mathbf{k}\cdot\mathbf{x}} \frac{1}{m^2 - k^2 - i\epsilon} \equiv \Delta(x)$$

15. Page 26, line 1: replace “the integral in” by “the integral is”

16. Page 34, eq. (4.18) and following: the arguments of T are three-vectors (boldface), not four-vectors.

17. Page 34: replace eq. (4.19) by

$$T(\mathbf{k}_1, \mathbf{k}_2; \mathbf{p}_1, \mathbf{p}_2) = \frac{\lambda}{\sqrt{4E_{p_1}E_{p_2}}} \frac{1}{\sqrt{(2\pi)^3 2E_{k_1}} \sqrt{(2\pi)^3 2E_{k_2}}}.$$

18. Page 39: replace eq. (4.43) by

$$\mathcal{M}_{ij} - \mathcal{M}_{ji}^* = i \sum_f \int d\phi_{n_f}(P_i; k_1^f, \dots, k_{n_f}^f) \mathcal{M}_{if} \mathcal{M}_{jf}^*$$

19. Page 39: replace eq. (4.45) by

$$i\lambda^2 \int d\phi_2(P_i; k_1, k_2) = \frac{i\lambda^2 |\mathbf{k}_1|}{16\pi E_{k_1}},$$

20. Page 40: replace eq. (4.46) by

$$-i \frac{d^4 q}{(2\pi)^4},$$

21. Page 40: replace eq. (4.47) by

$$\mathcal{M}_{2 \rightarrow 2}^{\text{1loop}} = -i \sum_{j=1}^3 \frac{\lambda^2}{2} \int \frac{d^4 q}{(2\pi)^4} \left[\frac{1}{m^2 - q^2 - i\epsilon} \frac{1}{m^2 - (P_j - q)^2 - i\epsilon} - \frac{1}{M^2 - q^2 - i\epsilon} \frac{1}{M^2 - (P_j - q)^2 - i\epsilon} \right] - C,$$

22. Page 40: replace eq. (4.48) by

$$\mathcal{M}_{2 \rightarrow 2}^{\text{1loop}} = -i \frac{\lambda^2}{2(2\pi)^4} \int d\mathbf{q} \int dq^0 \left[\frac{1}{E_q - q^0 - i\epsilon} \frac{1}{E_q + q^0 - i\epsilon} \times \frac{1}{E_q + 2E_{k_1} - q^0 - i\epsilon} \frac{1}{E_q - 2E_{k_1} + q^0 - i\epsilon} - \text{PV} \right],$$

23. Page 40: replace eq. (4.49) by

$$\mathcal{M}_{2 \rightarrow 2}^{\text{1loop}} = -\frac{\lambda^2}{16(2\pi)^3 E_{k_1}} \int \frac{d\mathbf{q}}{E_q} \left[\frac{1}{E_q + E_{k_1}} - \frac{1}{E_q - E_{k_1} - i\epsilon} - \text{PV} \right]$$

24. Page 41: replace eq. (4.50) by

$$\mathcal{M}_{2 \rightarrow 2}^{\text{1loop}} - \mathcal{M}_{2 \rightarrow 2}^{*\text{1loop}} = \frac{i\lambda^2 |\mathbf{k}_1|}{16\pi E_{k_1}}.$$

25. Page 49: replace eq. (5.52) by

$$\mathcal{L}_{\text{Weyl}} \rightarrow i(\xi_L^\dagger \sigma_\mu \partial^\mu \xi_L + \xi_R^\dagger \bar{\sigma}_\mu \partial^\mu \xi_R) = \mathcal{L}_{\text{Weyl}}$$

26. Page 58: replace eq. (6.27) by

$$F_{\mu\nu}(x)\psi(x) = \frac{i}{e} (D_\mu D_\nu - D_\nu D_\mu) \psi(x) \equiv \frac{i}{e} [D_\mu, D_\nu] \psi(x),$$

27. Page 59, after eq. (6.37): replace the lines from ‘‘This equation...’’ to ‘‘...four-vector function X^ν .’’ by:

‘‘This equation, however, has no solution. This is easily seen by taking the four-dimensional Fourier transform of eq. (6.37), and observing that the operator $k^2 g^{\mu\lambda} - k^\mu k^\lambda$ has no inverse, since k_λ is an eigenvector with vanishing eigenvalue’’.

28. Page 61, first line after eq. (6.52): replace “polarization” by “polarizations”
29. Page 62, line 2: replace “particle” by “particles”
30. Page 64, eq. (6.76): replace the last line by

$$= \frac{e^4}{16\pi s} \frac{1 + \sin^4 \frac{\theta}{2}}{\sin^2 \frac{\theta}{2}} d \cos \theta,$$

31. Page 69: replace eq. (7.2) by

$$\tau(N) = 885.7 \pm 0.8 \text{ s} \quad \tau(\mu) = (2.19703 \pm 0.00004) \times 10^{-6} \text{ s},$$

32. Page 87: in Section 8.3, the arguments of $\epsilon^{(\lambda)}$ and $P_{\mu\nu}$ are three-vectors (boldface), not four-vectors.
33. Page 87: replace eq. (8.34) by

$$A_\mu(x) = \frac{1}{(2\pi)^{3/2}} \int \frac{d\mathbf{k}}{\sqrt{2E_k}} \sum_{\lambda=0}^3 \left[a^{(\lambda)}(\mathbf{k}) \epsilon_\mu^{(\lambda)}(\mathbf{k}) e^{-ikx} + a^{\dagger(\lambda)}(\mathbf{k}) \epsilon_\mu^{(\lambda)*}(\mathbf{k}) e^{ikx} \right],$$

34. Page 88: replace eqs. (8.37-38) by

$$\left[a^{(\lambda)}(\mathbf{k}), a^{\dagger(\lambda')}(\mathbf{q}) \right] = -g^{\lambda\lambda'} \delta^{(3)}(\mathbf{k} - \mathbf{q}) \quad (0.1)$$

$$\left[a^{(\lambda)}(\mathbf{k}), a^{(\lambda')}(\mathbf{q}) \right] = \left[a^{\dagger(\lambda)}(\mathbf{k}), a^{\dagger(\lambda')}(\mathbf{q}) \right] = 0. \quad (0.2)$$

35. Page 88, first line after eq. (8.38): replace $a_k^{(\lambda)}$ by $a^{(\lambda)}(\mathbf{k})$
36. Page 88: replace eq. (8.41) and the following sentence by

$$|\mathbf{k}\rangle = \int d\mathbf{p} f_{\mathbf{k}}(\mathbf{p}) a^{\dagger(0)}(\mathbf{p})|0\rangle,$$

where $|0\rangle$ is the vacuum state, and $f_{\mathbf{k}}(\mathbf{p})$ is a packet function, centered around $\mathbf{p} = \mathbf{k}$.

37. Page 88: replace eq. (8.42) and the following sentence by

$$\begin{aligned} \langle \mathbf{k} | \mathbf{k} \rangle &= \int d\mathbf{p} d\mathbf{p}' f_{\mathbf{k}}(\mathbf{p}) f_{\mathbf{k}}^*(\mathbf{p}') \langle 0 | a^{(0)}(\mathbf{p}') a^{\dagger(0)}(\mathbf{p}) | 0 \rangle \\ &= -\langle 0 | 0 \rangle \int d\mathbf{p} |f_{\mathbf{k}}(\mathbf{p})|^2. \end{aligned}$$

We see that the states generated by $a^{\dagger(0)}(\mathbf{p})$ have negative norm, and must therefore be removed from the physical spectrum.

38. Page 92: replace eq. (8.64) by

$$v = \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}$$

39. Page 95: in the footnote, replace "dimension" with "dimensions".
 40. Page 106: replace eq. (11.5) by

$$\sum_{\text{pol}} |\mathcal{M}|^2 = \frac{G_F^2}{2} \text{Tr} [\gamma^\mu (1 - \gamma_5) (\not{p} + m_\mu) \gamma^\nu (1 - \gamma_5) \not{k}_2] \\ \times \text{Tr} [\gamma_\mu (1 - \gamma_5) \not{k}_1 \gamma_\nu (1 - \gamma_5) \not{k}].$$

41. Page 106: replace eq. (11.6) by

$$\sum_{\text{pol}} |\mathcal{M}|^2 = 2G_F^2 \text{Tr} [\gamma^\mu \not{p} \gamma^\nu \not{k}_2 (1 + \gamma_5)] \text{Tr} [\gamma_\mu \not{k}_1 \gamma_\nu \not{k} (1 + \gamma_5)].$$

42. Page 113: replace eq. (11.54), the following sentence, and eq. (11.55) by

$$\mathcal{M}(\nu q \rightarrow \nu q) = \frac{g^2}{16 \cos^2 \theta_w} \frac{1}{t - m_z^2} \\ \bar{u}(k_1) \gamma^\mu (1 - \gamma_5) u(p_1) \bar{u}(k_2) \gamma_\mu (V_q - A_q \gamma_5) u(p_2),$$

where $t = -2p_1 \cdot k_1$, and therefore

$$\sum_{\text{pol}} |\mathcal{M}(\nu q \rightarrow \nu q)|^2 = \left(\frac{g^2}{16 \cos^2 \theta_w} \right)^2 \frac{1}{(t - m_z^2)^2} \\ 2 \text{Tr} [\gamma^\mu \not{p}_1 \gamma^\nu \not{k}_1 (1 + \gamma_5)] \text{Tr} [\gamma_\mu \not{p}_2 \gamma_\nu \not{k}_2 (V_q^2 + A_q^2 + 2V_q A_q \gamma_5)].$$

43. Page 113: replace eq. (11.56) by

$$\mathcal{M}(\bar{\nu} q \rightarrow \bar{\nu} q) = \frac{g^2}{16 \cos^2 \theta_w} \frac{1}{t - m_z^2} \\ \bar{v}(p_1) \gamma^\mu (1 - \gamma_5) v(k_1) \bar{u}(k_2) \gamma_\mu (V_q - A_q \gamma_5) u(p_2),$$

44. Page 113: replace eq. (11.57) by

$$\sum_{\text{pol}} |\mathcal{M}(\bar{\nu} q \rightarrow \bar{\nu} q)|^2 = \left(\frac{g^2}{16 \cos^2 \theta_w} \right)^2 \frac{1}{(t - m_z^2)^2} \\ 2 \text{Tr} [\gamma^\mu \not{p}_1 \gamma^\nu \not{k}_1 (1 - \gamma_5)] \text{Tr} [\gamma_\mu \not{p}_2 \gamma_\nu \not{k}_2 (V_q^2 + A_q^2 + 2V_q A_q \gamma_5)].$$

45. Pages 113-114: replace eqs. (11.58-59) by

$$\sum_{\text{pol}} |\mathcal{M}(\nu d \rightarrow \mu u)|^2 = \left(\frac{g^2 |V_{ud}|}{8} \right)^2 \frac{1}{(t - m_w^2)^2} \\ 4 \text{Tr} [\gamma^\mu \not{p}_1 \gamma^\nu \not{k}_1 (1 + \gamma_5)] \text{Tr} [\gamma_\mu \not{p}_2 \gamma_\nu \not{k}_2 (1 + \gamma_5)]. \\ \sum_{\text{pol}} |\mathcal{M}(\bar{\nu} u \rightarrow \mu d)|^2 = \left(\frac{g^2 |V_{ud}|}{8} \right)^2 \frac{1}{(t - m_w^2)^2} \\ 4 \text{Tr} [\gamma^\mu \not{p}_1 \gamma^\nu \not{k}_1 (1 - \gamma_5)] \text{Tr} [\gamma_\mu \not{p}_2 \gamma_\nu \not{k}_2 (1 + \gamma_5)].$$

46. Page 114: replace the sentence between eq. (11.60) and eq. (11.61) by “where $s = 2p_1 \cdot p_2$, we have inserted a factor of $1/4$ to average over initial spin states, and we have assumed fermions to be massless. It is easy to show that the differences

$$\sum_{\text{pol}} \left[|\mathcal{M}(\bar{\nu}q \rightarrow \bar{\nu}q)|^2 - |\mathcal{M}(\nu q \rightarrow \nu q)|^2 \right]$$

$$\sum_{\text{pol}} \left[|\mathcal{M}(\bar{\nu}u \rightarrow \mu d)|^2 - |\mathcal{M}(\nu u \rightarrow \mu d)|^2 \right]$$

are linear in the initial parton momentum p_2 ; since s is also linear in p_2 , it follows that the parton cross section differences are independent of the momentum fraction z carried by the initial parton, $p_2 = zp$. Thus, using eq. (11.48) we find”

47. Page 123: replace eqs. (12.26-27) by

$$P(\nu_\beta \rightarrow \nu_\alpha; U) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta; U).$$

$$P(\nu_\alpha \rightarrow \nu_\beta; U^*) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta; U),$$

48. Page 124: replace eq. (12.32) by

$$\frac{L\Delta m^2}{4E} \simeq 1.27 \frac{\Delta m^2(\text{eV}^2) L(\text{km})}{E(\text{GeV})}.$$

49. Page 129: replace eq. (C.4) by

$$\gamma^\mu \gamma^\alpha \gamma^\beta \gamma_\mu = 4g^{\alpha\beta}$$