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LARGE RADIATIVE CORRECTIONS TO THE LOWEST-ORDER PROCESSES IN STANDARD MODEL

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Большие радиационные поправки к процессам низшего порядка в стандартной модели

Развита схема вычисления логарифмически-больших радиационных поправок *(рп)* к сечениям процессов стандартной модели (СМ) в борновском приближении. Большие величины *рп* обнаружены для $e^+e^- \to W^+W^-$, ZZ, $Z\gamma$ как для полных, так и для дифференциальных сечений, тогда как они отсутствуют для $\gamma\gamma$-столкновений. Это обуславливает «немонохроматичность» $e^{\pm}$-пучков на лептонных коллайдерах, аналогичную немонохроматичности γ-пучков, образуемых лазерной конверсией.

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Large Radiative Corrections to the Lowest-Order Processes in Standard Model

A scheme of calculation of logarithmically large radiations corrections (RC) to Born processes in the frame of the Standard Model (SM) for high energies is developed. Large values of RC are revealed for $e^+e^- \to W^+W^-$, ZZ, $Z\gamma$ both in the total cross-sections and in the differential ones, whereas they are absent in $\gamma\gamma$--collisions. This fact results in the effect of «nonmonochromatism» of $e^{\pm}$-beams at lepton colliders with fixed energies higher than $\sqrt{s} > 500$ GeV, which is analogous to nonmonochromatism of γ--beams produced by laser conversion.

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

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Production of gauge bosons W, Z in e^+e^--, γe-and $\gamma\gamma$-collisions at high energies is studied without difficulties. In addition, it is an important test for Standard Model as well as beyond it. The future accelerators (LEP2, VLEPP — Protvino) with the energies $\sqrt{s} = 200$ and 2000 GeV will provide us opportunity for performance of precision measurements of SM parameters. Due to this, the problem of RC in SM is actual and is discussed already for a recent time [1].

We have developed a simple technique [2] for extraction of logarithmically large RC, which was originally applied to electroweak interactions in [3] and is based on renormalization group formalism of quantum field theory, widely used in QCD [4]—[6]. This approached is developed independently by other groups too [7]—[12].

The main idea consists in consideration of the real and virtual electrons, positrons, photons, emitted by an incident particle A, as partons, and the taking into account of RC is reduced to calculation of a parton function, or structure one, $D_{A->a}(x, s)$, meaning the probability to find a parton a with the momentum fraction x and with the momentum squared up to s in "the parent" A. If we restrict ourselves by leading logarithmic contributions, we may use the Altarelli — Parizi — Lipatov equations [4]—[6] in order to define $D(x,s)$.

Thus, the proposed technique pretends to description of only the logarithmically large RC contributions, although in this case the accuracy of the order of a few per cents can be achieved.

Now we shall put down the differential cross-section for the process $A + B \to C + D$ in terms of partons [2]:

$$\frac{d\sigma^{A+B->C+D}}{d\Omega} = \sum_{a,b,c,d} \int dx_1 dx_2 dx_3 dx_4 D_{A->a}(x_1, s) D_{B->b}(x_2, s) \cdot \frac{d\hat{\sigma}^{a+b->c+d}}{d\Omega}(x_1 x_2 s) D_{c->C}(x_2, x_1 x_2 s) D_{d->D}(x_4, x_1 x_2 s), \quad (1)$$

where $d\hat{\sigma}/d\Omega$ is the cross-section of a subprocess $a + b \to c + d$, where A, B, a, b, are e^+e^-, γ; C, D, c, d are e^+, e^-, γ, W^+, W^-, Z; $\sqrt{s}$ is the initial energy. The total cross-section may be obtained with ease of integrating (1) over the angles.

Polarizations of the initial and final particles may be involved rather simply [2].

It should be noted that the contribution from interference between the initial and final particle radiations is not taken into account in the given above

expression. We shall show that in the one-loop approximation there is no logarithmically large RC from heavy final particles, $W^{\pm}$ do not contain logarithmically large terms too.

We introduce, for convenience, the following convolutions [2]

$$\varphi_{ij}(x, s) = \int_x^1 \frac{dy}{y} D_{A->i}(y, s) D_{B->j}\left(\frac{x}{y}, s\right). \quad (2)$$

Put down the following expressions for the SM lowest-order processes:

1. $e^+e^- \to W^+W^-$, ZZ

$$\frac{d\sigma^{e\bar{e}\to WW}}{d\Omega}(s) = \int dx_1 dx_2 D_{e->e}(x_1, s) D_{\bar{e}\to\bar{e}}(x_2, s) \frac{d\sigma^{e\bar{e}\to WW}}{d\Omega}(sx_1x_2)\chi(sx_1x_2) = \frac{1}{\rho}\int_1^{\rho} dx \varphi_{e\bar{e}}\left(\frac{x}{\rho}, \beta\right)\chi(sx)\frac{d\hat{\sigma}^{e\bar{e}\to WW}}{d\Omega}(sx), \quad (3)$$

where $x = x_1 x_2 \rho$, $\rho = s/(4m_W^2)$, $\beta = (2\alpha/\pi)(L - 1)$ and $L = \ln s/m_e^2$ is large value. Factor $\chi(s) = \left(\frac{\alpha(s)}{\alpha}\right)^2 = \left(1 - \frac{\alpha}{3\pi}L\right)^{-2}$ takes into account the "move" of coupling constant in subprocess cross section.

2. $\gamma e \to Ze$

$$\frac{d\sigma^{\gamma e\to W\nu}}{d\Omega}(s) = \int dx D_{e->e}(x, s)\frac{d\hat{\sigma}^{\gamma e\to W\nu}}{d\Omega}(sx), \quad (4)$$

3. $\gamma e \to Ze$

$$\frac{d\sigma^{\gamma e->Ze}}{d\Omega}(s) = \int dx_1 dx_3 D_{e->e}(x_1 s) D_{e->e}(x_3, x_1 s)\frac{d\hat{\sigma}^{e\gamma\to Ze}}{d\Omega}(x, s), \quad (5)$$

4. $e\bar{e} \to Z\gamma$

$$\frac{d\sigma^{e\bar{e}->Z\gamma}}{d\Omega}(s) = \frac{1}{\rho}\int_1^{\rho} dx \varphi_{e\bar{e}}\left(\frac{x}{\rho}, \beta\right)\frac{d\hat{\sigma}^{e\bar{e}->Z\gamma}}{d\Omega}(x) \quad (6)$$

5. $\gamma\gamma \to WW$

$$\frac{d\sigma^{\gamma\gamma->WW}}{d\Omega}(s) = \frac{d\sigma_0^{\gamma\gamma->WW}}{d\Omega}(s) + \int dx_1 dx_2 D_{\gamma->e}(x_1, s) D_{\gamma\to\bar{e}}(x_2, s)\chi(sx_1)\frac{d\hat{\sigma}^{e\bar{e}\to WW}}{d\Omega}(sx_1x_2)\chi(sx_2). \quad (7)$$

We specially have written the expression (3) in the form of convolution, where $\varphi_{e\bar{e}}(x)$ plays the role of lepton beam nonmonochromatism, like for the process 5, where cross-section is to be convoluted with the function of photon beam nonmonochromatism [14].

To find structure functions, we shall take the Altareli — Parizi — Lipatov equations:

$$D(x,\beta) = \delta(1-x) + \int_0^L \frac{d\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[D(y,\beta_t)P_e^e\left(\frac{x}{y}\right) + G(y,\beta_t)P_\gamma^e\left(\frac{x}{y}\right)\right];$$

$$\overline{D}(x,\beta) = \int_0^L \frac{d\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[\overline{D}(y,\beta_t)P_e^{\bar e}\left(\frac{x}{y}\right) + G(y,\beta_t)P_\gamma^{\bar e}\left(\frac{x}{y}\right)\right]; \qquad (8)$$

$$G(x,\beta) = -\frac{2}{3}\int_0^L \frac{d\alpha(t)}{2\pi} G(x,\beta_t) +$$

$$+ \int_0^L \frac{d\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y}\left[D(y,\beta_t)P_e^\gamma\left(\frac{x}{y}\right) + \overline{D}(y,\beta_t)P_e^\gamma\left(\frac{x}{y}\right)\right],$$

with the following notations: $D_{e^\pm \to e^\pm}(x,s) = D(x,\beta)$; $D_{e^\pm \to e^\mp}(x,s) = \overline{D}(x,\beta)$; $D_{e->\gamma}(x,s) = G(x,\beta)$.

On solving iteratively the (8), we obtain that with the required accuracy (1% for LEP2 where $\beta \approx 0.1$), the terms up to including β^2 are to be kept:

$$D(x,\beta) = \frac{1}{2}\beta\left[\left(1 + \frac{3}{8}\beta\right)(1-x)^{\beta/2-1} - \frac{1}{2}(1+x)\right],$$

$$\overline{D}(x,\beta) = \frac{1}{32}\frac{\beta^2}{x}\left[-2x(1+x)\ln\frac{1}{x} + \frac{1}{3}(1-x)(4 + 7x + 4x^2)\right], \qquad (9)$$

$$G(x,\beta) = \frac{1}{4}\frac{\beta}{x}(1 + (1-x)^2) + \frac{1}{64}\beta^2\left[(3 + 4\ln(1-x))\frac{1}{x}(1 + (1-x)^2) + \right.$$

$$\left. + 2(2-x)\ln x + \frac{2}{x}(1-x)(2x-3)\right].$$

or for the appropriate convolution,

$$\varphi_{e\bar e}(x,\beta) = \beta\left[\left(1 + \frac{3}{4}\beta\right)(1-x)^{\beta-1} - \frac{1}{2}(1+x)\right]. \qquad (10)$$

In fig. 1—6 the total and differential cross-sections as the functions of an initial energy are depicted for the processes 1—5, with and without taking into account of RC. As you can see, the values of RC are large for all processes, besides $\gamma\gamma \to W^+W^-$, where RC is practically absent in leading log approximation, is the exception. For the total

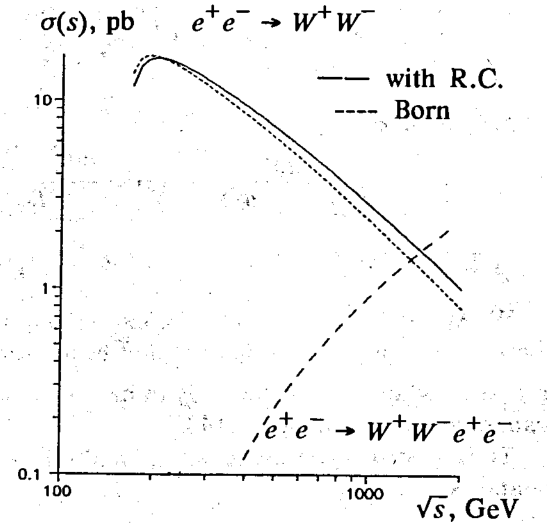

Fig.1. Dependence of the total cross-sections of two mechanisms of W^+W^- production at e^+e^- collisions from the total energy in c.m.s. frame $\sqrt{s}$.

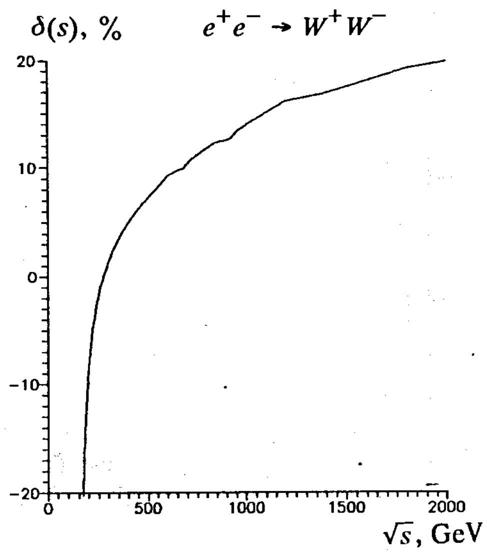

Fig.2. «Effetive» radiative correction (ERC) $\delta(s)$ dependence on $\sqrt{s}$ for the total cross section of the process $e^+e^- \to W^+W^-$.

cross-sections of the processes 1—5 the value of RC comprises $\approx$5—7% for LEP2 and $\approx$15—20% for $\sqrt{s} = 2$ TeV. Up to the LEP2 energy they are negative, then become positive. It is clearly observed in figs.2,3 for $\delta(s)$ defined as (we call them "Effective radiative corrections" (ERC))

$$\sigma(s) = \sigma_{Born}(s)(1 + \delta(s)) \qquad (11)$$

and for $\delta(s,\Omega)$ defined, in its turn, as

$$\frac{d\sigma}{d\Omega}(\Omega = \frac{d\sigma_{Born}}{d\Omega}(s)(1 + \delta(s,\Omega)). \qquad (12)$$

For differential cross-sections ERC are catastrophically large. For instance, for the processes 1 and the scattering angle $\pi/2$ they comprise more than 50%

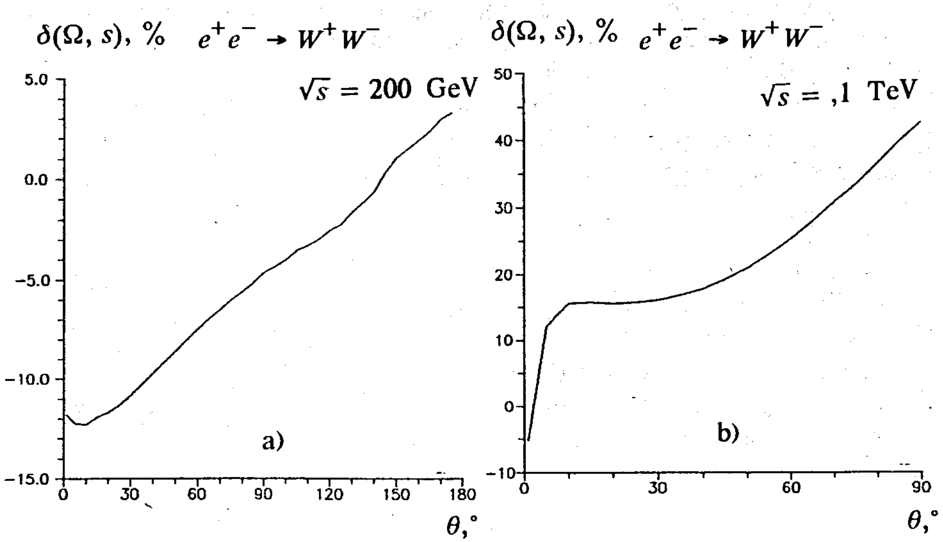

Fig. 3. a) ERC for $\delta(\Omega, s)$ for differential cross section $e^+e^- \to W^+W^-$. as a function of angle θ between the W^- and e^- momenta as $\sqrt{s} = 200$ GeV. b) The $\delta(\Omega, s)$ for $e^+e^- \to W^+W^-$ angular dependence for $\sqrt{s} = 1$ TeV.

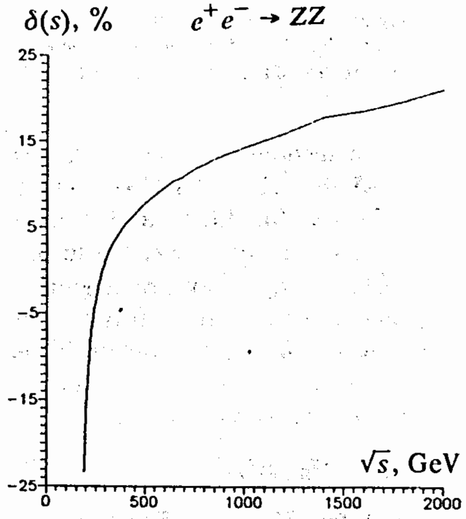

Fig.4.ERC $\delta(s)$ for the total cross section of the two Z production process $e^+e^- \to ZZ$.

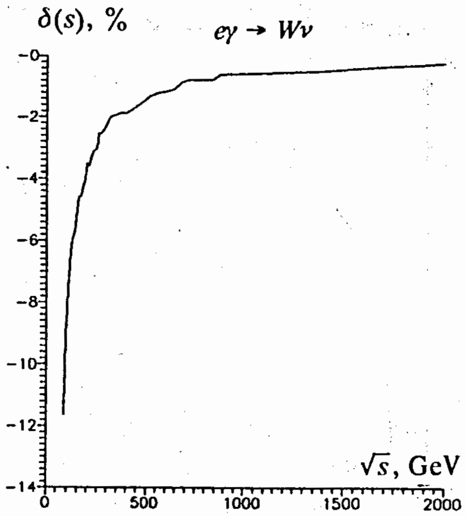

Fig.5. ERC-energy dependence for the single W production in the process $\gamma e \to W\nu$.

(see fig.2). It is explained by the fact that differential cross-sections are concentrated, practically, in the forward directions and fall very sharply beyond it.

We would like to note one interesting fact. If an experiment, by any reason, has cutoffs, then, generally speaking, arises the problem of the taking into account of other contribution for which final particles are not observed (excepting WW-production in the reaction $e\bar{e} \to WW$). So, when considering W-pair production in ee-collisions, we are to take into account also, for instance, the process $e\bar{e} \to WW$, $e\bar{e}$, which comes about via the transitions $e\bar{e} \to \gamma\gamma e\bar{e} \to WW\, e\bar{e}$ and the final leptons are not caught by detectors. Now the expression (3) is to be supplemented by the contribution from $\gamma\gamma \to WW$

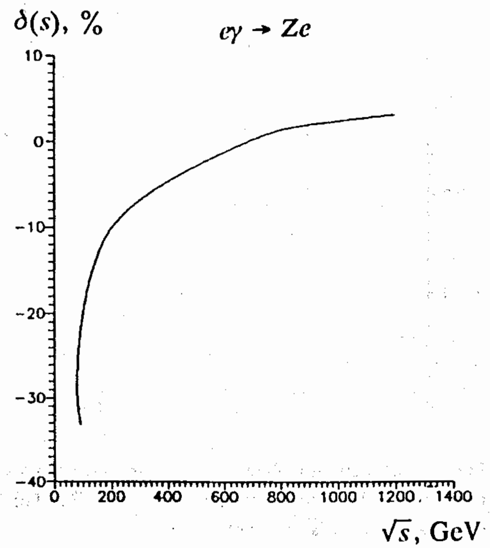

Fig.6. ERC-energy dependence for the single Z production in the process $\gamma e \to Ze$.

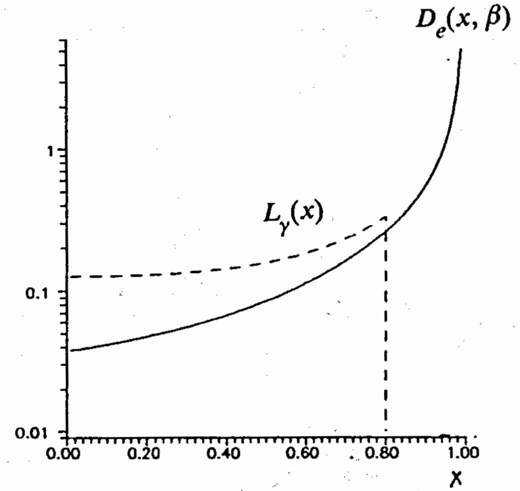

Fig.7. Dependence of structure function $D_e(x,\beta)$ on x for $\beta = 0.124$ ($\sqrt{s} = 200$ GeV) (solid line). Dashed line shows the dependence on $x = \omega/\varepsilon$ of the probability of backward Compton scattering of lazer beam on electron beam with energy ε.

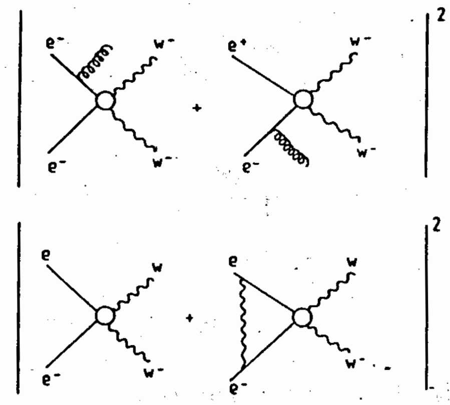

Fig.8. The lowest order diagrams which produce large RC: real and virtual photons emission by initial leptons.

$$\frac{d\sigma^{e\bar{e}\to WW}}{d\Omega}(s)=\int dx_1 dx_2 D_{e\to\gamma}(x_1,s)\times \tag{13}$$

$$\times\, D_{\bar{e}\to\gamma}(x_2,s)\,\frac{d\hat{\sigma}^{\gamma\gamma\to WW}}{d\Omega}(x_1 x_2 s)$$

which turns out to be dominant at $\sqrt{s} \approx$ 1— 2 TeV and comprises ≈ 2.7 pb, whereas the expression (3) gives ≈ 0.9 pb at this energy. Thus, under such observational conditions a lepton collider transforms into a photon one! The same situation may occur for the rest processes.

The quantity $\varphi_{e\bar{e}}$ plays just the same role of "nonmonochromatism" as that one for the real photon beams occuring as a result of laser conversion [14].

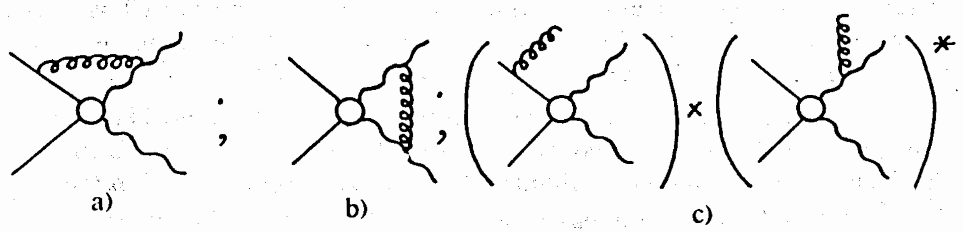

Fig.9. Initial particles radiation–final particle radiation interference diagrams: block-scheme.

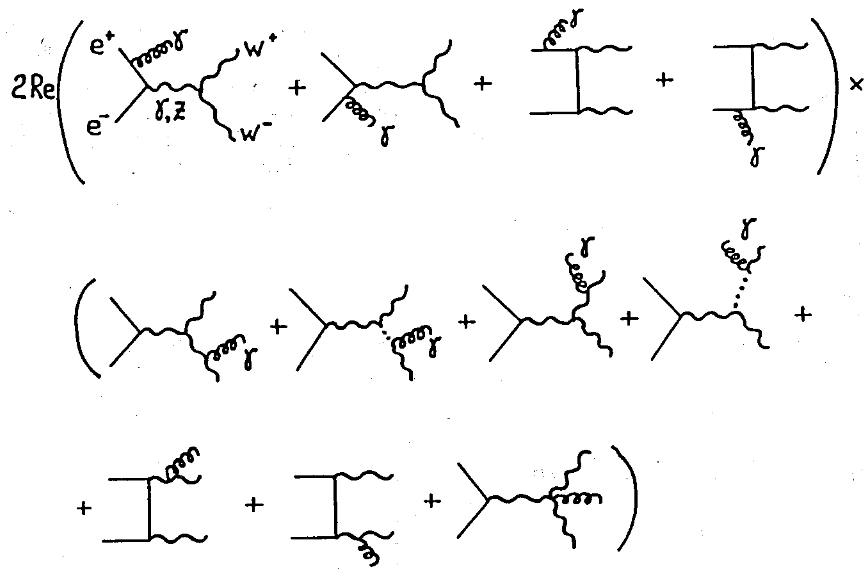

Fig.10. Diagrams of Fig. 9 in t'Hooft — Feynmann gauge.

In fig.7, for comparison, $\varphi_{e\bar{e}}$ together with the factor of real nonmonochromatism, taken from [14], are given.

Thus, we go to the discussion of RC, related to final heavy particles, $W^{\pm}$, and its interference with the initial ones. Let us discuss in detail the process $e\bar{e} \to WW$. The Feynman diagrams in the one-loop approximations (its total number is ≈ 200), involved in (3), which describe virtual corrections and take into account real photon radiation as well, are depicted in fig.8.

The diagrams in which a lepton and a W-boson as well as the final WW-bosons exchange a virtual photon, and, besides, interference of the amplitudes of real photon radiation by leptons and W-bosons is considered, as in fig.9, are not taken into account in (3). We shall show that its contribution does not contain large logarithms $L = \ln(s/m_e^2)$. It is numerically small and can be taken into account by the so-called K-factor. The contributions of the diagrams in which a virtual photon does not interact with leptons (figs.9b) as well as ones referred to the squared amplitude of real photon radiation by W-bosons are also finite in the limit $m_e \to 0$ and can be introduced into the K-factor.

The assertion on absence of the contribution of the diagrams like those, depicted in fig.9, to a total cross-section is evident. Really, interference between the Born amplitude and the amplitudes of fig.9c is an odd function of $\cos\theta = c$, $\theta = \widehat{\vec{p}_-, \vec{q}_-}$ and, on integrating, it gives zero. As for the differential cross-sections, the situation, in large, has common with that for the process

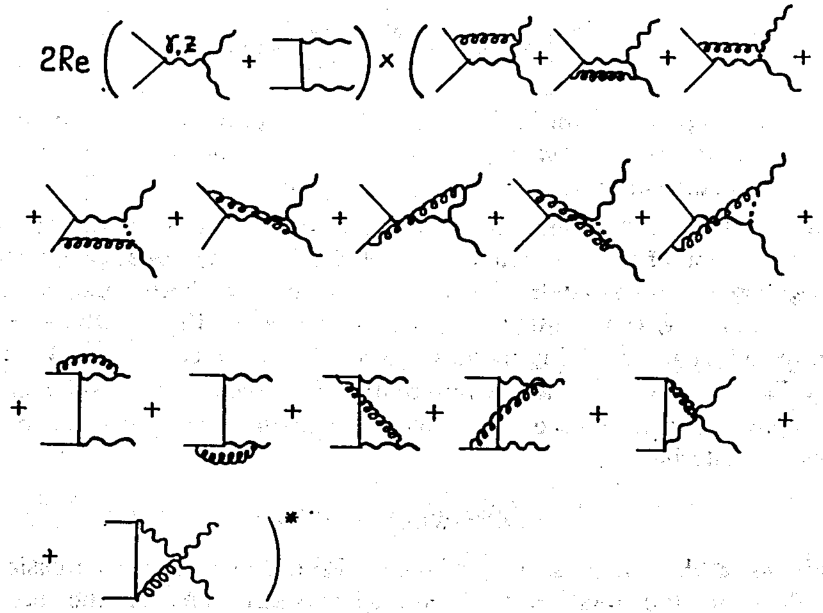

Fig.11. One-loop diagrams of initial-final virtual photon radiation in t'Hooft — Feynmann gauge.

$e^+e^- \to \mu^+\mu^-$, where the taking into account of the box diagrams, like in fig.9c, forces the occurrence of charge-odd asymmetry for the quantity

$$A(\theta) = \frac{d\sigma(\theta) - d\sigma(\pi - \theta)}{d\sigma(\theta) + d\sigma(\pi - \theta)},$$

which dies not contain $\ln(s/m_e^2)$. This fact can be illustrated in the lowest order of PT. The soft real photon radiation, depicted in fig.10, can be calculated and gives the well-known result:

$$d\sigma^{soft} = -\frac{\alpha}{2\pi^2}\int_0^{\Delta\varepsilon}\frac{d^3k}{\omega}\left(\frac{p_+}{p_+k} - \frac{p_-}{p_-k}\right)\left(\frac{q_+}{q_+k} - \frac{q_-}{q_-k}\right)d\sigma_o =$$
$$= \frac{4\alpha}{\pi}\left[\ln\left(\frac{2\Delta\varepsilon}{\lambda}\right)\ln\frac{1+\beta^2-2\beta c}{1+\beta^2+2\beta c} + 0(1)\right]d\sigma_0, \qquad (14)$$

where λ is the photon "mass", β is W-boson velocity in c.m.s.

The hard photon radiation $d\sigma^{hard}$ can be taken into account, in the leading logarithm approximation, using the replacement $\ln(2\Delta\varepsilon/\lambda) \to \ln(\varepsilon/\lambda)$.

Finally, the parameter λ will be dropped when considering the virtual corrections, for which a logarithmic contribution comes about from the region of "soft" virtualities ($|k^2| < m_W^2$, see fig.11):

$$d\sigma^{\text{virt}} = \frac{4\alpha}{\pi}\left[\ln\frac{\lambda}{\varepsilon}\ln\frac{1+\beta^2-2\beta c}{1+\beta^2+2\beta c} + 0(1)\right]d\sigma_0. \tag{15}$$

The virtual photon contribution to the interference between the initial and final particles radiations gives the logarithmically large contribution (15).

The net contribution $d\sigma_{\text{soft}} + d\sigma_{\text{hard}} + d\sigma_{\text{virt}}$ is finite at $m_e \to 0$

In the conclusion, we would like to stress once more that a simple technique for consideration of logarithmically large RC in the lowest-order processes of SM is proposed and grounded by one-loop calculations here. Unexpectedly large values of RC contributions to the processes $e\bar{e} \to WW, ZZ, Z\gamma$; $\gamma e \to Ze$ are revealed. However, RC is practically absent in the processes $\gamma\gamma \to W^+W^-$, $\gamma e \to W^-\nu$. Large values of RC in differential cross-sections are explained by catastrophically rapid falls of the latters beyond the region of forward and backward scattering.

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