A new version of carlomat that allows to generate automatically the Monte Carlo programs dedicated
to the description of the processes $e^+ e^- \rightarrow$ hadrons at low center-of-mass energies is presented. The
program has been substantially modified in order to incorporate the photon–vector meson mixing terms and
to make possible computation of the helicity amplitudes involving the Feynman interaction vertices
of new tensor structures, like those predicted by the Resonance Chiral Theory or Hidden Local Symmetry
model, and the effective Lagrangian of the electromagnetic interaction of the nucleons. Moreover, a
number of new options have been introduced in the program in order to enable a better control over the
effective models implemented. In particular, they offer a possibility to determine the dominant production
mechanisms of the final state chosen by the user.

Program summary

Program title: carlomat, version 3.0
Catalogue identifier: AEDQ_v3.0
Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AEDQ_v3_0.html
Program obtainable from: CPC Program Library, Queen’s University, Belfast, N. Ireland
No. of lines in distributed program, including test data, etc.: 71596
No. of bytes in distributed program, including test data, etc.: 2804246
Distribution format: tar.gz
Programming language: Fortran 90/95.
Computer: All.
Operating system: Linux.
Catalogue identifier of previous version: AEDQ_v2.0

Does the new version supersede the previous version?: Yes

Nature of problem: Predictions for reactions of low energy $e^+ e^- \rightarrow$-annihilation into final states containing
pions, kaons, light vector mesons, one or more photons and light fermion pairs within the Standard
Model and effective models inspired by the Resonance Chiral Theory or Hidden Local Symmetry model.
Description of the electromagnetic production of nucleon pairs within the effective Lagrangian approach.

Solution method: As in former versions, a program for the Monte Carlo (MC) simulation of $e^+ e^- \rightarrow$ hadrons
at low energies is generated in a fully automatic way for a user specified process. However, the user
is supposed to select a number of options and adjust arbitrary parameters in the main part of the MC
computation program in order to obtain possibly the best description of experimental data. To this end, the
user can also easily supplement her/his own formulae for s-dependent vector meson widths or running
couplings by appropriately modifying corresponding subroutines.
1. Introduction

Hadronic contributions to the vacuum polarization are the major factor that influences precision of theoretical predictions for the muon anomaly $\alpha_{\mu}$ and plays an important role in the evolution of the fine structure constant $\alpha(Q^2)$ from the Thomson limit to high energy scales. Improving the precision of predictions for the muon anomaly becomes vital in the prospect of forthcoming measurements in Fermilab that should reduce the experimental error of $\alpha_{\mu}$ to 0.14 parts per million, while the better precision of $\alpha(m_Z^2)$ would be important for the precision data analysis from the future high energy $e^+e^-$ collider, which would most probably include a giga-Z option. Because of the breakdown of predictive power of the perturbative QCD at low momentum transfer, the hadronic contributions to the vacuum polarization are determined, with the help of dispersion relations, from the energy dependence of the total cross section of electron–positron annihilation into hadrons, $\sigma_{e^+e^- \rightarrow \text{hadrons}}(s)$. Below the $J/\Psi$ production threshold, $\sigma_{e^+e^- \rightarrow \text{hadrons}}$ must be measured and confronted with theoretical predictions of some effective model for the low energy hadron physics.

There are two QCD inspired theoretical frameworks which seem to be applicable in this context: the Resonance Chiral Theory (RChT) [1] and the Hidden Local Symmetry (HLS) model [2], which were proven to be essentially equivalent [3]. For example, the HLS model allowed for a quite satisfactory simultaneous description of most hadronic $e^+e^-$-annihilation channels in the low energy range, including $\phi$-resonance and 10 decay widths, mostly radiative ones, of light mesons and allowed to resolve the inconsistency between the $e^+e^-$-annihilation to $\pi^+\pi^-$ and the $\tau^-$-decay to $\pi^+\pi^0\nu_\tau$ [4], [5]. The hadronic currents based on RChT were implemented in Tauola, a $\tau$-decay Monte Carlo (MC) generator [6], and used for description of the $\tau$ lepton decay into two or three pseudoscalar mesons that constitute 88% of the $\tau$ hadronic decay width in Ref. [7] and later improved for $\tau^\pm \rightarrow \pi^{\mp}\pi^0\pi^\mp\nu_\tau$ decay mode in Ref. [8] which allowed to successfully model the one-dimensional distributions measured by the BaBar collaboration.

The number of Feynman diagrams in the framework of RChT or HLS model grows quite fast with the number of particles in the final state of $e^+e^- \rightarrow$ hadrons. In particular, in the presence of one or a few photon–vector meson mixing terms, it can easily reach a hundred thousand already for $e^+e^- \rightarrow \pi^0\pi^0$. Obviously, preparation of a reliable MC generator for such a process is rather tedious task, unless the process of code writing is fully automatized. The first step toward the automatic generation of the MC programs

Reasons for new version: Processes of $e^+e^- \rightarrow$ hadrons in the energy range below the $J/\Psi$ threshold cannot be described in the framework of perturbative quantum chromodynamics. The scalar electrodynamics which has been implemented in carlomat 2.0 [1] does not provide a satisfactory description either. The most promising theoretical frameworks in this context are the Resonance Chiral Theory or Hidden Local Symmetry model which, among others, involves the photon–vector meson mixing and a number of vertices of rather complicated Lorentz tensor structure that is not present in the Standard Model or scalar QED. Already at low energies, the hadronic final states may consist of several particles, such as pions, kaons, or nucleons which can be accompanied by one or more photons, or light fermion pairs such as $e^+e^-$. The number of Feynman diagrams of such multiparticle reactions grows substantially with increasing numbers of interaction vertices and mixing terms of the effective models. Therefore, it is highly desirable to automatize the calculations. At the same time, new program options should provide the user with an easy way of implementing her/his own changes in the program in order to better fit the experimental data.

Summary of revisions: The code generation part of the program has been substantially modified in order to incorporate the photon–vector meson mixing and calls to new subroutines for computation of the helicity amplitudes of the building blocks and complete Feynman diagrams which contain new interaction vertices and mixing terms. Many subroutines have been modified in order to incorporate the $q^2$–dependent couplings and vector meson widths. A number of options have been introduced in order to give a better control of the effective model implemented.

Restrictions: As in previous versions of the program the number of particles is limited to 12 which exceeds typical numbers of particles of the exclusive low energy $e^+e^-$-annihilation processes. However, in the presence of photon–vector meson mixing, the Feynman diagrams proliferate, for example, with currently implemented Feynman rules, there are 90672 diagrams of $e^+e^- \rightarrow 3(\pi^+\pi^-)$. Hence, the compilation time of generated code may become very long already for processes with a smaller number of the final state particles. Many couplings of the effective models are not known with good enough precision and must be adjusted in consecutive runs of the program in order to obtain a satisfactory description of the experimental data.

Running time: Depends on the selected process. Typical running time for the code generation varies from a fraction of a second for, e.g., $e^+e^- \rightarrow \pi^+\pi^-K^+K^-$ to about 2 min for $e^+e^- \rightarrow 3(\pi^+\pi^-)$. It may become substantially longer for processes with more particles in the final state. The execution time necessary to produce the appended test output files for $e^+e^- \rightarrow \pi^+\pi^-\mu^+\mu^-\gamma$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma$ was 13s and 4s, respectively. The code generation for both processes took a fraction of a second time for each process.

References:

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for description of reactions $e^+e^- \rightarrow$ hadrons was already made in carlomat_2.0 [9], in which the Feynman rules of the scalar electrodynamics (sQED) were implemented in addition to those of the Standard Model (SM). It allowed to effectively describe the electromagnetic (EM) interaction of charged pions which, at low energies, can be considered as being point like particles, see, e.g., [10]. However, the charged pion form factor that would allow to account for the bound state nature of the particle was not implemented in carlomat_2.0. In the present paper, a new version, labeled with 3.0, of a program carlomat [11], [9] is described, which to large extent should meet the requirements of automatic code generation for MC simulation of the low energetic $e^+e^-$-annihilation into hadrons in the framework of the effective models.

The paper is organized in the following way. In Section 2, the implementation of new Feynman rules in the program is described. New options which have been implemented in the program to give the user a better control over the model are described in Section 3. Finally, the instructions for preparation for running and usage of the program are given in Section 4.

2. New Feynman rules implemented in the program

In this section, the implementation of the Feynman rules of the HLS model that are relevant for the description of $e^+e^- \rightarrow$ hadrons in the low energy range in carlomat_3.0 is described. Most of the rules can be derived from the Lagrangian pieces of Appendix C of Ref. [4]. The Lagrangian of EM interaction of spin 1/2 nucleons implemented in the program is described in Section 2.3.

2.1. Photon–vector meson mixing

The topology generator of carlomat takes into account only triple and quartic vertices, therefore the mixing should be added in subroutine checktop, where topologies of diagrams are confronted with the implemented Feynman rules. The procedure was described in detail in Ref. [11]. For the sake of clarity let us remind here, that every topology in carlomat is divided into two parts, each being checked against the Feynman rules separately. This is done by consecutive calls to subroutine genpart that combines two (three) particles into the third (fourth) leg of a triple (quartic) Feynman vertex which is then folded with the adjacent Feynman propagator to form an off-shell particle. The latter is represented by an array of spinors, polarization vectors or scalars, whose elements are labeled with different combinations of the polarization indices of the particle spinors or polarization vectors of which they are formed. At this point, if the particle mixing is present, a new subroutine mixpl is called to check whether the propagator of the off-shell particle can be mixed with some other propagator or not, if so, a new off-shell particle is formed. The particle with mixing is appropriately tagged in order not to be mixed again, because, according to Fig. 1, the mixing term contains an extra power of the electric charge $e$ and therefore should be considered as the next to leading-order correction. This procedure is being repeated until finally two off-shell particles are formed, corresponding to both parts of the considered topology. Then, a modified subroutine matchzk is called which checks, whether the particles can be matched in the Feynman diagram with the Feynman propagator or, if none of them has been mixed yet, with some of the mixing terms of Fig. 1.

In spite of being conceptually quite simple, the implementation of particle mixing required substantial changes in the code-generation part of the program. Moreover, new subroutines bbbk and bbnd have been written to compute, respectively, the polarization vectors of the off-shell particle and helicity amplitudes of the Feynman diagrams in the case of mixing.

![Fig. 1](attachment:image1.png)

Fig. 1. The photon–vector meson mixing diagrams implemented in the current version of the program; $\rho_1$ and $\rho_2$ stand for $\rho(1450)$ and $\rho(1700)$, respectively.

![Fig. 2](attachment:image2.png)

Fig. 2. Triple vertices of the photon $A^\pm$ or vector meson $V^\pm$, $V = \rho^0, \omega, \phi$, interaction with the pseudoscalar meson pair $P P$, $P = \pi^+, K^+, K^0$, of the same form as that of the triple vertex of sQED.

![Fig. 3](attachment:image3.png)

Fig. 3. Triple vertices of the pion interaction with photons or vector mesons, where, in the top right corner, $V = \rho^0, \omega$, in the bottom right corner $P = \pi^0$ and $V = \rho^0$ or $P = \pi^+$ and $V = \rho^0$.

2.2. Interaction vertices

The triple and quartic interaction vertices of the HLS model that are implemented in carlomat_3.0 are depicted in Figs. 2–4, where all the particle four momenta are assumed to be incoming to the vertex and $s^{\mu\nu\rho\sigma}$, with $s^{0123} = 1$, is the totally antisymmetric Levi-Civita tensor. A number of new subroutines for computation of the building blocks and complete amplitudes of the Feynman diagrams containing vertices of new tensor structure have been written. The implementation of calls to the new subroutines required some changes in the code-generation part of the program which concerned mainly subroutine genpart.

The triple vertices of the photon $A^\pm$ or vector meson $V^\pm$ interaction with the pseudoscalar meson pair $P P$ which have the form similar to the triple vertex of sQED are shown in Fig. 2. The only difference is the replacement

$$e \rightarrow e f_{\rho\rho\rho}(q^2) \quad \text{and} \quad e \rightarrow f_{\rho\omega\omega}(q^2),$$

(1)

where $V = \rho^0, \omega, \phi, \rho_1, \rho_2$ and $P = \pi^+, K^+, K^0$. Although couplings of $\rho_1 = \rho(1450)$ and $\rho_2 = \rho(1700)$ to other particles are hard to define on the basis of existing data [12], the interaction vertices $\rho^0 \pi^+ \pi^-$ and mixing terms $\gamma - \rho_i, i = 1, 2$, have been included in the program just to enable tests of their possible influence on some observables, e.g., on the pion form factor, where they play a role.

Subroutines ppakk, appkk and papkk for the computation of building blocks of the Feynman diagrams, and ppmd, appmd and papmd for the computation of the helicity amplitudes in the sQED of carlomat_2.0 have been all supplemented with an option i.g, which allows to take into account the $q^2$-dependent couplings of (1). Subroutines ppakk and papmd have been additionally supplied with an option 1with, that gives a possibility to include the s-dependent width of a vector meson. The use of both options is explained in Section 3.

Triple interaction vertices of the HLS model that have a form different from that of the triple vertices of the SM or sQED are depicted in Fig. 3. New subroutines that have been written in order to compute the corresponding building blocks and helicity
amplitudes are: pvvkk, pvvmd, vvpkk and vvpmd. All of them include the running-coupling option ig, and the first one, whose output is an array of four vectors corresponding to all possible helicities of the scalar and vector particles they are composed of, includes in addition the running-width option iwidth.

The quartic interaction vertices of the HLS model implemented in the current version of the program are shown in Fig. 4. The vertices in the first row have the same tensor form as the quartic vertex of the sQED or the quartic vertices of the Nambu–Goldstone boson–gauge boson interaction of the SM, which have been implemented already in the first version of carlomat. Hence, the corresponding building blocks and helicity amplitudes can be computed with modified subroutines vsvskk, vsvsmd, vsvvsk, vsvsmd, vsvvmd, vsvvsk, vsvvmd, vsvvsk, vsvvmd which have been all supplied with the running-coupling option ig. Subroutines vsvskk, vsvvsk have been moreover supplemented with the running-width option iwidth. The tensor form of the vertices in the second row of Fig. 4 is different. Therefore, the corresponding building blocks and helicity amplitudes are computed with newly written subroutines pppvkk, ppvvmd, vppppk and vpppmd.

2.3. Electromagnetic interaction of nucleons

The Lagrangian of EM interaction of spin 1/2 nucleons has the following form:

$$\mathcal{L}_{\text{ANN}} = eA_0\bar{N}(p') [\gamma^\mu F_1(Q^2) + \frac{i}{2m_N} \gamma^\mu q F_2(Q^2)] N(p),$$

where $$\sigma^{\mu\nu} = \frac{1}{2}[\gamma^\mu, \gamma^\nu]$$, with $$\gamma^\mu$$, $$\mu = 0, 1, 2, 3$$, being the Dirac matrices, $$q = p - p'$$ is the four momentum transfer, $$F_1(Q^2)$$ and $$F_2(Q^2)$$ are the form factors and $$Q^2 = -q^2$$. The form of Eq. (2) is similar to that of the effective Lagrangian of the Wtb interaction given by Eq. (4) of Ref. [9]. Due to this fact, the implementation of the corresponding Feynman rules for the nucleon–photon interaction was straightforward. To compute the corresponding building blocks and helicity amplitudes the following new subroutines have been written: ankk, anmd, nank, nnd, nnak, and the calls to them have been appropriately implemented in subroutine genpart. The form factors $$F_1(Q^2)$$ and $$F_2(Q^2)$$ have been adopted from PHOKARA [13] with the help of an interface subroutine nuclff_phok. In this way, the MC simulations of processes involving the EM production of the nucleon pairs have become possible.

3. New program options

New options which have been added in the program to give the user a better control over the implemented models for the description of the electron–positron annihilation into hadrons at low energies are explained below.

All subroutines that are used to compute the building blocks or the complete helicity amplitudes of the Feynman diagrams of Figs. 2–4 have been supplied with the running-coupling option the name of which is formed by adding a prefix i to the name of the corresponding coupling, as the name is created in exactly the same way at the stage of code generation. The options are to be specified in subroutine couplm, where they are defined below the assignment instruction for each particular coupling.

```c
if (igmrh == ...) then
    block in subroutine runcoupl.
end if
```

where choices 1, 2, ..., corresponding to different running couplings $$f(q^2)$$ of Figs. 1–4 should be added by the user as extra else if (ig == ...) then blocks in subroutine runcoupl.

The block must contain an assignment for a double complex variable rg in terms of the four momentum transfer squared $$q^2$$ and any other physical parameters that are available in module inprms. The actual form of the four momentum transfer $$q$$ is determined automatically from the four momentum conservation in the corresponding interaction vertex at the stage of code generation. Many couplings of the RYT or HLS model are not known well enough and therefore must be adjusted in consecutive runs of the program in order to obtain satisfactory description of the experimental data. If there are no hints as to the form of the running couplings $$f(q^2)$$ then it is recommended to set the corresponding running-coupling option to 0, which means that the fixed coupling is to be used in the computation. The user can also modify any of the fixed couplings by changing the corresponding assignments in couplm, where the couplings are defined in terms of the physical parameters of module inprms.

The subroutines for computation of the four vectors representing vector mesons have been in addition supplied with the running-width option iwidth_name, i.e. igmrh, igmom, igmph, igmr1, igmr2 for the running width of $$\rho_0$$, $$\omega$$, $$\phi$$, $$\rho_1$$, $$\rho_2$$, respectively:

```c
iwidth_name=0/1,2,3  
```

where choices 1, 2, 3 refer to different running-width options in subroutine runcoupl which again can easily be extended by the user. The options are controlled from carlomat, the main part of the MC computation program.

The main part of the MC computation program carlomat contains a few flags: iarho, iaome, iaphi, iarho1 and iarho2 that allow to switch off and on the photon mixing with $$\rho$$, $$\omega$$, $$\phi$$, $$\rho_1$$ and $$\rho_2$$ vector mesons without a need of running the code-generation program anew, provided that the corresponding mixing terms were included in a file vertices.dat when the MC code was generated. This gives a possibility to determine the dominant production mechanisms of the final state considered by the user.

In order to give a better control over the mixing contributions to a given process, subroutines bblk and bbdn are equipped with the option:

```c
iwdgt=0/1,2,3  
```

where choices 0, 1, 2, 3 refers to different running-width options in subroutine runcoupl which again can easily be extended by the user.
The actual names for that option in carlocom are: imrho, imome, imphi, imrh1, imrh2 for the $\rho^0$, $\omega$, $\phi$, $\rho_1$, $\rho_2$ meson, respectively. The complex factor $c_i,j = 1, 2, \ldots$ is given by
\[ c_i = w_i e^{i\varphi_i f_i(q^2)}, \tag{3} \]
where $w_i$ is a positive weight, $\varphi_i$ is an angle in degrees, which should be both specified for each possible particle mixing term in the main program for the MC computation carlocom, and $f_i(q^2)$ is a possible four momentum transfer dependence that is defined in subroutine weightfactor. Actually only three simple dependences corresponding to $iwgt=1, 2, 3$ are currently defined in weightfactor, but the user can easily add more options by implementing new else if ($iwgt == \ldots$) then conditions.

An important new option in the program, which allows to test the EM gauge invariance for processes with one or more external photons, is $igauge$ in carlocom:
\[
igauge=1,2,\ldots/\text{else if the gauge invariance is/is not to be tested}, \tag{4}
\]
where 1, 2, ..., is the number of a photon, counting from left to right, whose polarization four vector is replaced with its four momentum.

To illustrate how this option can be used in practice, consider the following radiative processes:
\[
e^+e^- \rightarrow \pi^+\pi^-\mu^+\mu^-, \tag{4} \]
\[
e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-, \tag{5}
\]
Taking into account the Feynman rules of SM, without the Higgs couplings to electrons and muons, sQED, the $\gamma - \gamma^*$ mixing of Fig. 1 and the vertices: $\gamma \gamma^* \pi^-\pi^-$ and $\rho^0 \pi^+\pi^-$ of Fig. 2, $\gamma^*\gamma^*\gamma^*$ and $\pi^0\rho^0\rho^0$ of Fig. 3 and $\gamma\rho^0\rho^0\gamma$ and $\gamma\rho^0\pi^0\pi^-$ of Fig. 4, processes (4) and (5) receive contribution from, respectively, 209 and 774 Feynman diagrams. If, in addition, the vertices $\pi^+\gamma\rho^0\pm$ of Fig. 3 are included then the number of diagrams of processes (4) and (5) grows, respectively, to 231 and 968. The cross sections of processes (4) and (5) at $\sqrt{s} = 1$ GeV, with the following cuts on the angles between the photon and a lepton $\theta_{\gamma l}$, the photon and a pion $\theta_{\gamma\pi}$ and the photon energy:
\[
\theta_{\gamma l} > 5^\circ, \quad \theta_{\gamma\pi} > 5^\circ, \quad E_\gamma > 10$ MeV, \tag{6}
\]
are presented in Table 1. The cross sections without (with) contribution from the $\pi^+\gamma\rho^0\pm$ interaction vertices of Fig. 3 are printed in the first (second) column for each process. If $igauge=1$ then the cross section drops by about 32 orders of magnitude, which means that the EM gauge invariance works perfectly well. However, if the vertices $\pi^+\gamma\rho^0\pm$ of Fig. 3 are included then the EM gauge invariance is not so perfect any more. For process (4) this is caused by the two Feynman diagrams depicted in Fig. 5. To justify this statement, let us denote the four momenta of particles of process (4) by $p_1, p_2, \ldots, p_7$, from left to right consecutively, and consider the EM gauge invariance test for the amplitudes of the diagrams (a) and (b) of Fig. 5, which means in practice that the photon polarization four vector is replaced with its four momentum. Neglecting the i factors, which are the same for both amplitudes, and skipping polarization indices the amplitudes read:
\[
M_a = g^2 \varepsilon_{12} \varepsilon_{\mu
u\rho\gamma} p_{12\alpha} (-q_\rho) \frac{q_\mu q_\nu}{M^2} \times \varepsilon_{65\sigma} \varepsilon_{\rho\gamma\delta} (-p_{56\sigma}) \varepsilon_{37} \gamma \tag{7}
\]
\[
= \frac{e^2 g^2}{q^2-M^2} \varepsilon_{\mu \nu \rho \gamma} \varepsilon_{\mu \nu \gamma \delta} \varepsilon_{12} \varepsilon_{37} \varepsilon_{46} \varepsilon_{56} \varepsilon_{p_3} \varepsilon_{p_4} \varepsilon_{p_5} \varepsilon_{p_6} \varepsilon_{p_7} \varepsilon_{p_8} \tag{8}
\]
where $\varepsilon_{12} (\varepsilon_{37})$ is the polarization four vector representing the $e^+e^-\gamma (\mu^-\mu^+)\gamma$ vertex contracted with the adjacent photon propagator, $M^2 = m_\gamma^2 - im_\gamma T_\gamma$ is the complex $\gamma$ meson mass parameter, $p_{12} = p_1 + p_2$, $p_{65} = p_5 + p_6$, $q = p_5 + p_6 + p_7$, and $r = p_{56} + p_4 + p_7$ are four momenta of intermediate virtual photons and $\rho^0$ mesons, and the coupling $g = ef_{\pi-A_\rho} (q^2) = ef_{\pi-A_\rho} (q^2) = ef_{\pi-A_\rho} (r^2)$ has been assumed to have a fixed value. In the second row of Eqs. (7) and (8), use has been made of the fact that, in the EM gauge invariance test, the scalars $s_{37}$ and $s_{47}$ representing the $\pi^+\gamma\pi^-\gamma$ and $\pi^-\gamma\pi^+\gamma$ vertex multiplied with the adjacent pion propagator, take the following form:
\[
s_{37} = e^2 \frac{(p_3 + p_7 - (-p_3)) \varepsilon_{\mu} (p_3)}{(p_3 + p_7)^2 - m_\pi^2} \bigg|_{(p_3) \rightarrow p_3} = e \frac{2p_3 \cdot p_7}{2p_3 \cdot p_7} = e, \tag{9}
\]
\[
s_{47} = e^2 \frac{(-p_4 - (p_4 + p_7)) \varepsilon_{\mu} (p_4)}{(p_4 + p_7)^2 - m_\pi^2} \bigg|_{(p_4) \rightarrow p_7} = -e \frac{2p_4 \cdot p_7}{2p_4 \cdot p_7} = -e. \tag{10}
\]
It is clear from the form of Eqs. (7) and (8) that amplitudes $M_a$ and $M_b$ neither vanish separately nor cancel each other, contrary to the amplitudes of the other 20 Feynman diagrams of process (4) which also contain the vertices $\pi^+\gamma\rho^0\pm$. Although that degree of gauge invariance violation should not play any role in practice, such effects should be treated with great care, as they may become sizable in some regions of the photon phase space. Therefore, it is recommended to use the $igauge$ option whenever new interaction vertices are tested against the program.
4. Preparation for running and program usage

carlomat_3.0 is distributed as a single tar.gz archive carlomat_3.0.tgz which can be downloaded from: http://kk.us.edu.pl/carlomat.html. When untared with a command
tar -xzvf carlomat_3.0.tgz
it will create directory carlomat_3.0 with sub directories: code_generation, mc_computation, carlolib, test_output and test_output0.

Although carlomat_3.0 is dedicated to the description of low energy e^+e^- scattering, interfaces to the parton density functions are kept. Therefore, files mstwpdf.f of MSTW[14] and Cteq6Pdf.f and cteq6l.tbl of CTEQ6[15] are also included in the current distribution of the program, but grids must be downloaded from the web page of MSTW, see readme file or [9] for details. If the program will not be run for the hadron scattering processes the user can comment lines contained between ckk_had> and ckk_had< in crosskk.f and parfixkk.f, and comment or remove references to mstw_interface.o, mstwpdf.o, Cteq6Pdf.o, cteq6f_interface.o from makefile in mc_computation.

Preparation for running requires basically the same steps as in carlomat_2.0. They are recollected below for user's convenience.

- Choose a Fortran 90 compiler in makefile's code_generation and mc_computation and compile all the routines of carlolib with the same compiler as that chosen in mc_computation;
- Specify the process and required options in carlomat.f and execute make code from the command line in code_generation;
- Go to mc_computation, choose the center of mass energy and required options in carlocom.f and execute make mc in the command line.

Whenever the Fortran compiler is changed, or a compiled program is transferred to another computer with a different processor, all the object and module files should be deleted by executing the commands:

```bash
rm *.o
rm *.*.mod
```

and the necessary steps of those listed above should be repeated.

The basic output of the MC run is written to file tot_name, where name is created automatically if the assignment for character variable

```plaintext
prcsme='auto'
```

in carlomat.f is not changed to arbitrary user's defined name. The output files for processes (4) and (5) with the preselected parameters and options should reproduce those delivered in directory test_output0.

If the differential cross sections/distributions are required then set

```plaintext
idin=1
```

in carlocom.f. The number of distributions to be calculated must be specified in distrib.f and their parameters should be defined in calcdis.f. The output will be stored in data files dbf_name and dlf_name which can be plotted with boxes and lines, respectively, with the use of gnuplot. When the run is finished all output files, except for test that may contain information relevant in case of unexpected program stop, are moved to directory test_output.

As in former versions of the program, there is a possibility of generating the unweighted events. It is governed by the option imc that is available in carlomat.

The code generation for processes (4) and (5) takes a fraction of a second time. The MC computation of the cross sections of Table 1 in 10 iterations, with a maximum of 200000 calls to the integrand each, takes 142 s and 43 s time, respectively, for (4) and (5) on processor Intel® Core™ i5-4200M CPU @ 2.50 GHz with a 64 bit Intel Fortran compiler.

Acknowledgments

This project was supported in part with financial resources of the Polish National Science Centre (NCN) under grant decision No. DEC-2011/03/B/ST6/01615. The author is grateful to Fred Jegerlehner for providing the Feynman rules of the HLS model and to Henryk Czyż and Szymon Tracz for providing the results of fits of the nucleon form factors.

References