DESY-03-099
SFB/CPP-03-16
hep-ph/0308014
July 2003

ee4fγ

A program for $e^+e^- \to 4f, 4f\gamma$ with nonzero fermion masses[1]

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Abstract

A computer program ee4fγ for calculating cross sections of any four fermion final state of e^+e^--annihilation at high energy and the corresponding bremsstrahlung reaction that is possible in the framework of the Standard Model is presented. As the fermion masses are arbitrary, the cross sections can be computed without any collinear cut, the on-shell top quark production can be studied and the Higgs boson exchange can be incorporated in a consistent way. The program can be used as a Monte Carlo generator of unweighted events as well.

[1] Work supported in part by the Polish State Committee for Scientific Research (KBN) under contract No. 2 P03B 045 23, by the European Community's Human Potential Program under contract HPRN-CT-2000-00149 Physics at Colliders and by DFG under Contract SFB/TR 9-03.

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PROGRAM SUMMARY

Title of program: `ee4f`γ

Version: 1.0 (June 2003)

Catalogue identifier:

Program obtainable from: CPC Program Library or on request by e-mail from the authors

Licensing provisions: none

Computers: all

Operating systems: Unix/Linux

Programming language used: `FORTRAN 90`

Memory required to execute with typical data: 4.0 Mb

No. of bits in a word: 32

No. of bytes in distributed program, including test data, etc.: 1.284 Mb

Distribution format: ASCII

Keywords: e^+e^- annihilation, SM, lowest order four fermion reactions, bremsstrahlung, nonzero fermion masses

Nature of physical problem
Description of all $e^+e^- \to 4$ fermions and corresponding bremsstrahlung reactions that are possible in the Standard Model (SM) to lowest order and with nonzero fermion masses at center of mass energies typical for next generation linear colliders. Such reactions are relevant, typically, for W-pair or intermediate mass Higgs boson production and decay.

Method of solution
Matrix elements are calculated with the helicity amplitude method. The phase space integration is performed numerically utilizing a multi-channel Monte Carlo method.

Restrictions on complexity of the problem
No higher order effects are taken into account, except for assuming the fine structure constant and the strong coupling at the appropriate scale and partial summation of those one particle irreducible loop corrections which are inducing the (fixed) finite widths of unstable particles.

Typical running time
The running time depends strongly on a selected channel and desired precision of the result. The results of the appended test run have been obtained on a 800 MHz Pentium III processor with the use of Absoft `FORTRAN 90` compiler in about 9 minutes. In order to obtain a precision level below one per mille a few million calls to the integrand are required. This results in a typical running time of several hours.

LONG WRITE-UP

1 Introduction

Precise tests of the Standard Model (SM) that will become possible at future high luminosity e^+e^- linear colliders like TESLA [1], the NLC [2], or the JLC [3] require adequate high precision of theoretical predictions. To meet this requirement is a challenge, as the complexity of perturbative calculation increases while going to higher energy and higher luminosity. The spectrum of possible reactions involves among others the four fermion channels with possible real photon emission. These reactions, which are of particular relevance for W-pair or intermediate mass Higgs boson production and decay, receive contributions from several to about one thousand Feynman diagrams already at the tree level of the SM.

In this article, a technical documentation of a numerical program `ee4f`γ is presented which allows for computer simulation of all the four fermion reactions

$$e^+(p_1) + e^-(p_2) \to f_1(p_3) + \bar{f}_2(p_4) + f_3(p_5) + \bar{f}_4(p_6), \tag{1}$$

and the corresponding bremsstrahlung reactions

$$e^+(p_1) + e^-(p_2) \to f_1(p_3) + \bar{f}_2(p_4) + f_3(p_5) + \bar{f}_4(p_6) + \gamma(p_7), \tag{2}$$

where f_i, $i = 1, 2, 3, 4$ make up a four fermion final state possible in the SM and the particle momenta have been indicated in the parentheses. The physics contents of the program has been discussed in earlier works [4]–[6], where the details on the underlying physics, the method of calculation and physical results obtained with `ee4f`γ have been presented.

In the approximation of massless fermions, all possible four fermion channels for $e^+e^- \to 4$f have been investigated in [7] (`EXCALIBUR`) and those for $e^+e^- \to 4\text{f}\gamma$ in [8] (`RacoonWW`). `ee4f`γ makes possible computations with nonzero fermion masses. Keeping nonzero fermion masses will be important in cases if predictions at the 1% accuracy level are required [4]–[6]. Finite masses also provide a natural regularization of distributions which become singular in the massless limit. Massive calculations thus provide reliable benchmarks for massless calculations with cuts. The latter are much simpler and hence much faster than calculations with massive codes.

`ee4f`γ may be considered as a building block (the soft plus hard bremsstrahlung part) of a complete $O(\alpha)$ calculation of the processes $e^+e^- \to 4$f. Such calculations have been attempted in [9] (see also [10]) and have been completed in the double pole approximation for W-pair production [11] (`RacoonWW`) and [12] (`KORALW/YFSWW`) (see also [13] (`EEWW`)). The double pole approximation incorporates the one-loop corrections for on-shell W-pair production [14] and the subsequent decay of W's into fermion-pairs [15].

Several existing programs, some of them being general purpose packages, may be utilized for tree-level calculations of $e^+e^- \to 4$f, $4\text{f}\gamma$ with massive fermions. These are `GRACE/BASES` [16], `MADGRAPH/HELAS` [17], `CompHEP` [18] (squared matrix element technique), `WPHACT` [19], `NEXTCALIBUR` [20] (initial state radiation photons generated via the structure function approach), `HELAC/PHEGAS` [21] (recursive Dyson-Schwinger equation approach), `WRAP` [22] (`ALPHA` [23] algorithm), `O'Mega/WHIZARD` [24] and `AMEGIC++` [25]. Most of the codes work on the basis of

helicity amplitudes and some use the structure function approach to generate the photons. Except for `NEXTCALIBUR`, which is specialized to $e^+e^- \to 4f$, all other programs allow to generate and evaluate amplitudes for other type of processes. For more details and comparisons we refer to the *Four Fermion Working Group Report* [26].

The main advantage of the present program is that it allows for relatively fast computation cross sections of both (1) and (2). As fermion masses are not neglected, the cross sections can be calculated without any kinematical cuts. A number of options have been implemented in the program which make possible calculation of the cross sections while switching on and off different subsets of the Feynman diagrams. Besides of a possibility of taking into account solely the electroweak contributions, or switching off the Higgs boson exchange diagrams, the program allows also for a simplified treatment of reactions (1), (2) by utilizing two different narrow width approximations: for W bosons

$$\begin{aligned} e^+(p_1) + e^-(p_2) &\to W^+(p_{34}) + W^-(p_{56}) && (3)\\ &\to f_1(p_3) + \bar{f}_2(p_4) + f_3(p_5) + \bar{f}_4(p_6), && (4) \end{aligned}$$

and for a $\bar{t}$-quark

$$\begin{aligned} e^+(p_1) + e^-(p_2) &\to t(p_3) + \bar{t}(p_{456}) && (5)\\ &\to t(p_3) + \bar{b}(p_4) + f_3(p_5) + \bar{f}_4(p_6). && (6) \end{aligned}$$

2 Scheme of the calculation

The necessary matrix elements of reactions (1) and (2) are calculated with the helicity amplitude method described in [27] and [4] and phase space integrations are performed with the Monte Carlo (MC) method.

In order to improve the convergence of the MC integration the most relevant peaks of the matrix element squared related to the Breit-Wigner shape of the W, Z, Higgs and top quark resonances as well as to the exchange of a massless photon or gluon have to be mapped away. As it is not possible to find out a single parametrization of the multi-dimensional phase space which would allow to cover the whole resonance structure of the integrand, it is necessary to utilize a multi-channel MC approach [28]. The reader is referred to [29] for more details on the multi-channel MC algorithm, on which the MC integration and event generation is based.

The basic phase space parametrizations which are used in the program are listed below. The 4 particle phase space of reaction (1) is parametrized in 2 different ways:

$$\mathrm{d}^7 Lips = (2\pi)^{-7} \frac{|\vec{p_3} + \vec{p_4}|}{4\sqrt{s}} \,\mathrm{d}\cos\theta_{34}\mathrm{d}s_{34}\mathrm{d}s_{56}\mathrm{d}PS_2\left(s_{34}, m_3^2, m_4^2\right)\mathrm{d}PS_2\left(s_{56}, m_5^2, m_6^2\right), \quad (7)$$

$$\mathrm{d}^7 Lips = (2\pi)^{-7} \frac{|\vec{p_3}|}{4\sqrt{s}} \,\mathrm{d}\cos\theta_{3}\mathrm{d}s_{456}\mathrm{d}s_{56}\mathrm{d}PS_2\left(s_{456}, s_{45}, m_6^2\right)\mathrm{d}PS_2\left(s_{56}, m_5^2, m_6^2\right), \quad (8)$$

where $s = (p_1 + p_2)^2$, $s_{ij\ldots} = (p_i + p_j + \ldots)^2$ and $\mathrm{d}PS_2(p^2, q^2, r^2)$ is a two particle (subsystem) phase space element defined by

$$\mathrm{d}PS_2\left(p^2, q^2, r^2\right) = \delta^4\left(p - q - r\right)\,\frac{\mathrm{d}^3 q}{2q^0}\,\frac{\mathrm{d}^3 r}{2r^0} = \frac{|\vec{q}|}{4\sqrt{p^2}}\mathrm{d}\Omega, \quad (9)$$

with $\vec{q}$ being the momentum and Ω the solid angle of one of the particles (subsystems) in the relative center of mass system, $\vec{q}+\vec{r}=0$. Momenta $\vec{p_3}+\vec{p_4}$, $\vec{p_3}$ and the corresponding polar angles θ_{34}, θ_3 in Eqs. (7) and (8) are defined in the c.m.s. frame with a positive direction of the z axis determined by $\vec{p_1}$. Using the rotational symmetry with respect to the e^+e^- beam axis, the azimuthal angles of $\vec{p_3}+\vec{p_4}$ in Eq. (7) and $\vec{p_3}$ in Eq. (7) are set to zero which reduces the dimension of the phase space integral from 8 to 7. Parametrization (7) covers the kinematical situation where the final state fermions make up two 2-particle subsystems of approximately equal invariant mass. Similarly, the parametrization (8) corresponds to the production of a 1- and 3-particle subsystems with the latter decaying again into 1- and 2-particle subsystems.

The 5 particle phase space of reaction (2) is parametrized in 3 different ways. Parametrizations

$$\begin{aligned}
\mathrm{d}^{10}Lips &= (2\pi)^{-10}\,\frac{E_7}{2}\,\mathrm{d}E_7\mathrm{d}\cos\theta_7\;\mathrm{d}PS_2\left(s',s_{34},s_{56}\right)\mathrm{d}s_{34}\mathrm{d}s_{56} \\
&\times\;\mathrm{d}PS_2\left(s_{34},m_3^2,m_4^2\right)\mathrm{d}PS_2\left(s_{56},m_5^2,m_6^2\right), \qquad (10)\\
\mathrm{d}^{10}Lips &= (2\pi)^{-10}\,\frac{E_7}{2}\,\mathrm{d}E_7\;\mathrm{d}\cos\theta_7\mathrm{d}PS_2\left(s',s_{456},m_3^2\right)\mathrm{d}s_{456}\mathrm{d}s_{56} \\
&\times\;\mathrm{d}PS_2\left(s_{456},s_{56},m_4^2\right)\mathrm{d}PS_2\left(s_{56},m_5^2,m_6^2\right), \qquad (11)
\end{aligned}$$

with $s'=(p_1+p_2-p_7)^2$ and the photon energy E_7 and solid angle Ω_7 being defined in the c.m.s., cover the initial state photon emission. The final state photon emission is covered by the following phase space parametrization

$$\begin{aligned}
\mathrm{d}^{10}Lips &= (2\pi)^{-10}\frac{\lambda^{1/2}(s,s_{347},s_{56})}{8s} \\
&\times\;\frac{1}{8}\mathrm{d}s_{347}\mathrm{d}s_{56}\mathrm{d}\cos\theta_{347}\mathrm{d}E_3\mathrm{d}E_7\mathrm{d}\Omega_3\mathrm{d}\phi_{37}\mathrm{d}PS_2\left(s_{56},m_5^2,m_6^2\right), \qquad (12)
\end{aligned}$$

where the polar angle θ_{347} of the momentum $\mathbf{p}_3+\mathbf{p}_4+\mathbf{p}_7$ is defined in the c.m.s.; the energy E_3 and spherical angle Ω_3 of the final state particle that radiates a photon, the photon energy E_7 and the azimuthal angle ϕ_{37} with respect to momentum of the radiating particle are defined in the frame where $\mathbf{p}_3+\mathbf{p}_4+\mathbf{p}_7=0$. Parametrizations (10–12) are also used with different permutations of external particle momenta and we have made use of the rotational symmetry with respect to the beam axis in order to reduce the dimension of integration from 11 to 10.

Invariant masses $s_{ijk\ldots}$ in Eqs. (7)–(12) should possibly correspond to virtuality of propagators of the gauge bosons, Higgs boson and/or top quarks. The peaks related to the propagators are then smoothed out by performing suitable mappings [29].

3 Description of the program

`ee4f`γ is a package written in `FORTRAN 90`. It consists of 97 files including a makefile. They are stored in one working directory. The user should specify the physical input parameters in module `inprms.f` and select a number of options in the main program `ee4fg.f`.

3.1 Program input

The default values of the input parameters and options used in the program are those specified below.

3.1.1 Physical parameters

The initial physical parameters to be specified in module `inprms.f` are the following.

Boson masses and widths (GeV):

- `mw=80.423` GeV, the W mass,
- `gamw=2.118` GeV, the W width,
- `mz=91.1876` GeV, the Z mass,
- `gamz=2.4952` GeV, the Z width,
- `mh=115.0` GeV, the Higgs mass,
- `gamh=0` GeV, the Higgs width. If `gamh = 0`, then the Higgs width is calculated according to the lowest order prediction of the SM.

The electroweak (EW) mixing parameter `sw2` is then calculated from

```
sw2 = 1-mw2/mz2
```

with

- `mw2 = mw**2` and `mz2 = mz**2` in the fixed width scheme,
- `mw2 = mw**2 - i*mw*gamw` and `mz2 = mz**2 - i*mz*gamz` in the complex mass scheme.

Coupling constants:

- `ralp0 = 137.03599976,` the inverse of the fine structure constant in the Thomson limit,
- `gmu=1.16639`$\times 10^{-5}$ GeV^{-2}, the Fermi coupling constant,
- `alphas=0.1172`, the strong coupling constant at scale `mz`.

The inverse of the fine structure constant at scale `mw`, `ralpw`, is then calculated from

```
ralpw=4.44288293815837/(2*sw2*gmu*mw**2).
```

Fermion masses and widths:

- `me = 0.510998902` MeV, `game = 0` MeV, for the electron,

- `mmu = 105.658357` MeV, `gammu = 0` MeV, for the muon,
- `mtau=1.77699` GeV, `gamtau = 0` GeV, for a tau lepton,
- `mu = 5` MeV, `gamu = 0` MeV, for an up quark
- `md=9` MeV, `gamd = 0` MeV, for a down quark,
- `mc=1.3` GeV, `gamc = 0` GeV, for a charm quark,
- `ms=150` MeV, `gams = 0` MeV, for a strange quark,
- `mt=174.3` GeV, `gamt = 1.5` GeV, for a top quark,
- `mb=4.4` GeV, `gamb = 0` GeV, for a bottom quark.

No. of colors and conversion constant:

- `ncol=3`, the number of colors,
- `convc=0.389379292`$\times 10^{12}$ fb GeV^2, a conversion constant.

3.1.2 Main options

The following main options should be selected in the main program `ee4fg.f`.

- The number of different center of mass (CMS) energies `ne`
  `ne = 1`. *Recommended if unweighted events are to be generated.*
- The actual values of the CMS energies in the array `aecm` of size `ne`:
  `aecm=(/500.d0/)`.
- The final state of (1) by selecting a value of `iproc` corresponding to a specific channel from the list contained in the file, *e.g.*
  `iproc=1`
  corresponds to $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu$. The bremsstrahlung is then calculated for the same channel.
- Whether or not to calculate the Born cross section, `iborn = 1 (yes) / else (no)`, with `ncall0` calls to the integrand
  `iborn = 1`
  `ncall0 = 100000`. *Recommended No of calls is a few millions.*
- Scan the Born cross section with `nscan0` calls, `iscan0 = 1(yes)/else(no)`, in order to find the dominant kinematical channels, adjust integration weights and find out the maximum value of the cross section
  `iscan0 = 1`. *This option is strongly recommended.*
  `nscan0 = 2000`. *A few thousands is recommended.*

- Whether or not to calculate the soft bremsstrahlung cross section, `isoft = 1 (yes) / else (no)`, with `ncalls` calls to the integrand
  `isoft = 1`
  `ncalls = 100000`. *Recommended No of calls is a few millions.* The integration weights are the same as those used for the Born cross section.

- Whether or not to calculate the hard bremsstrahlung cross section, `ihard = 1 (yes) / else (no)`, with `ncallh` calls to the integrand
  `ihard = 1`
  `ncallh = 100000`. *Recommended No of calls is a few millions.*

- Scan the hard bremsstrahlung cross section with `nscanh` calls, `iscanh = 1(yes)/else(no)`
  `iscanh = 1`. *This option is strongly recommended.*
  `nscanh = 2000`. *A few thousands is recommended.*

- Generate the unweighted events or not, `imc = 1(yes)/else(no)`?
  `imc = 0`.
  No standard event record is used. If `imc = 1`, then the final state particle momenta of the accepted unweighted events are printed in file `events.dat`.

- Include the Higgs boson exchange, `ihiggs = 1(yes)/else(no)`?
  `ihiggs = 1`

- Calculate the electroweak contributions only, `iew = 1(yes)/else(electroweak + QCD Feynman diagrams)`?
  `iew = 0`.

- Whether or not to calculate approximated cross section of (1) `itopa = 1 (yes) / else (no)`, with `ncalla` calls to the integrand, relevant only for top quark pair production with an on-shell top quark
  `itopa = 0`
  `ncalla = 20000`. *Recommended No of calls is a few hundred thousands.*

- Whether or not to calculate approximated cross section of (3) `iwwa = 1 (yes) / else (no)`, relevant only for W-pair production
  `iwwa = 0`
  This uses an analytic formula and does not require MC integration.

- Choose the scheme: `ischeme = 1(complex mass scheme)/else(fixed width scheme)`
  `ischeme = 0`

- If `ischeme=1`, then should `alpha_W` be complex `(iaplw=1)` or real `(ialpw=0)`?
  `ialpw=0`.

3.1.3 Auxiliary options

- Choose gauge: `iarbg = 0(unitary gauge)/1(arbitrary linear gauge)`, relevant only for the nonradiative top quark production
  `iarbg = 0`

- If `iarbg=1`, then choose gauge parameters ($\xi \geq 10^{16}$ corresponds to the unitary gauge):
  `ksia=1.d0`
  `ksiz=1.d16`
  `ksiw=1.d16`

- Specify the soft photon energy cut:
  `ecut=1.d0`

- Impose cuts, `icuts > 0(yes)/else(no)?`
  `icuts = 1`

- If `icuts = 1`, then specify the kinematical cuts:

  - `ctlb = 0.985` – cosine of the charged lepton-beam angle,
  - `ctll = 1` – cosine of the angle between charged leptons,
  - `ctlq = 1` – cosine of the charged lepton-quark angle,
  - `ctgb = 0.985` – cosine of the photon-beam angle,
  - `ctgl = cos(5./180*pi)` – cosine of the photon-charged lepton angle,
  - `ctgq = cos(5./180*pi)` – cosine of the photon-quark angle,
  - `ecutg = ecut` GeV – minimum hard photon energy,
  - `ecutl = 5` GeV – minimum charged lepton energy,
  - `ecutq = 0` GeV – minimum quark energy,
  - `mqq = 10` GeV – minimum invariant mass of a quark pair,
  - `mll = 0` GeV – minimum invariant mass of a charged lepton pair,

- If `icuts > 1`, then specify the kinematical cuts on a final state electron or positron:

  - `theb=5` – minimum angle of a final state electron and/or positron with respect to the beam.

- Calculate distributions, `idist = 1(yes)/0(no)?`
  `idis=0`

- If `idis = 1`, then specify parameters of the distributions:
  `nbs = (/ n1, ..., n8/)` – numbers of bins in each distribution.
  The corresponding lower and upper bounds of the distribution arguments
  `xmin = (/ xl1, ..., xl8/)` – lower bounds,
  `xmax = (/ xu1, ..., xu8/)` – upper bounds,
  must be specified below in the same file. Constants `xli, xui` should be of type `real(8)` and `ni` of type `integer`. The number of desired distributions and the maximum number of bins, `nbmax = max{n1, ..., n8}` should be specified in a module `distribs.f`.

- The maximum of the fully differential cross section `crmax`, relevant only if `iscan0 = 0` or `iscanh = 0`,
  `crmax=1000.`

3.2 Routines of ee4fg

The main program ee4fg, each subroutine, function or module are located in a file named the same way as the routine itself, except for subroutines eev, eve and vee, contained in gwwv.f, and functions: srr, src and scc, contained in dotprod.f. The package consists of the following routines.

- SUBROUTINE boost – returns a four vector boosted to the Lorentz frame of velocity $-\mathbf{v}$.
- SUBROUTINE cancuts – checks if generated particle momenta satisfy kinematical cuts.
- SUBROUTINE carlos – the MC integration routine.
- SUBROUTINE couplsma – returns SM couplings.
- FUNCTION cross – calculates cross sections of (1) and (2).
- FUNCTION crosstopa – calculates approximated cross section of (1) for top quark pair production with an on-shell top quark in the narrow anti-top width approximation.
- The MAIN PROGRAM ee4fg.
- SUBROUTINE cseeww – returns the total unpolarized cross section of on-shell W-pair production.
- SUBROUTINE cutscrit – specifies the class of a process (1), *i.e.*, whether the process is purely leptonic, semileptonic, hadronic, etc.
- MODULE cutvalues – contains values of kinematical cuts.
- FUNCTION ddilog – calculates the real part of a dilogarithm for real arguments.
- MODULE distribs – contains parameters of distributions.
- MODULE drivec – contains driving flags and some kinematical variables.
- SUBROUTINE eeee – returns a contraction of a quartic gauge boson coupling with four complex four vectors.
- FUNCTION eee – returns a contraction of a triple gauge boson coupling with three complex four vectors.
- SUBROUTINE eeff1 – returns the squared matrix element averaged over initial spins and summed over final spins and colors of $e^+e^- \to f\bar{f}$.
- SUBROUTINE eeffffcc1a – returns the squared matrix element averaged over initial spins and summed over final spins and colors of (1) for a charged current processes, iproc < 11 or $14 \leq$ iproc < 21, and the matrix element squared in the double W resonance approximation in arbitrary linear gauge.
- SUBROUTINE eeffffcc1 – returns the same as eeffffcc1a but in the unitary gauge.

- SUBROUTINE eeffffcc2 – returns the squared matrix element averaged over initial spins and summed over final spins and colors of (1) for the mixed charged and neutral current processes, $11 \leq$ iproc < 14. These matrix elements can be also obtained with eeffffnc3.

- SUBROUTINE eeffffcc3 – returns the same as eeffffcc2 for $e^+e^- \to \bar{\nu}_e\nu_e e^+e^-$, iproc $=$ 21.

- SUBROUTINE eeffffgid1 – returns the squared matrix element averaged over initial spins and summed over final spins and colors of the neutral current processes (2) containing identical leptons, $401 \leq$ iproc < 406.

- SUBROUTINE eeffffgid2 – returns the same as eeffffgid1 for the neutral current processes (2) containing identical quarks, $406 \leq$ iproc < 412.

- SUBROUTINE eeffffgid3 – returns the same as eeffffgid1 for the neutral current processes (2) containing identical electron neutrinos, iproc $= 412$.

- SUBROUTINE eeffffgnc1 – returns the squared matrix element averaged over initial spins and summed over final spins and colors of the neutral current processes (2) containing neither virtual gluons nor an external electron, $21 \leq$ iproc < 201.

- SUBROUTINE eeffffgnc2 – returns the same as eeffffgnc1 for the neutral current processes (2) not containing virtual gluons, $201 \leq$ iproc < 211.

- SUBROUTINE eeffffgnc3 – returns the same as eeffffgnc1 for the neutral current processes (2) containing $\bar{\nu}_e\nu_e$-pair, $211 \leq$ iproc < 301.

- SUBROUTINE eeffffgnc3 – returns the same as eeffffgnc1 for the mixed charged and neutral current processes (2), $301 \leq$ iproc < 401.

- FUNCTION eefffffgs – returns the soft bremsstrahlung correction for any channel of (1).

- SUBROUTINE eeffffid1 – the same as eeffffgid1 for (1).

- SUBROUTINE eeffffid2 – the same as eeffffgid2 for (1).

- SUBROUTINE eeffffid3 – the same as eeffffgid3 for (1).

- SUBROUTINE eeffffnc1 – the same as eeffffgnc1 for (1).

- SUBROUTINE eeffffnc2 – the same as eeffffgnc2 for (1).

- SUBROUTINE eeffffnc3 – the same as eeffffgnc3 for (1).

- SUBROUTINE eeffffnc4 – the same as eeffffgnc4 for (1).

- SUBROUTINES eev, eve and vee (contained in gwwv.f) – return contractions of a triple gauge boson coupling with two polarization vectors leaving, respectively, the third, second and first Lorentz index uncontracted.

- SUBROUTINE fefefef – returns matrix elements of the form $\bar{u}_1 \not{V}_1 S_{F1} \not{V}_2 S_{F2} \not{V}_3 u_2$, where Γ_i, $i = 1, 2, 3$, and S_{Fj}, $j = 1, 2$, denote the SM gauge boson-fermion coupling and Feynman propagator of a fermion, respectively.

- `SUBROUTINE fefefefh` – returns the same as `fefefef` including contributions of the Higgs boson exchange.
- `SUBROUTINE fefef` – returns matrix elements of the form $\bar{u}_1 \not{V}_1 S_{F1} \not{V}_2 u_2$.
- `SUBROUTINE fefefh` – returns the same as `fefef` including contributions of the Higgs boson exchange.
- `SUBROUTINE fef` – returns matrix elements of the form $\bar{u}_1 \not{V}_1 u_2$.
- `SUBROUTINE fefh` – returns the same as `fef` including contributions of the Higgs boson exchange.
- `SUBROUTINE ffvgnew` – returns four vectors representing contributions resulting from an attachment of a photon to the SM gauge boson-fermion vertex including a possible Higgs boson exchange contribution.
- `SUBROUTINE fhf` – returns matrix elements $g_{Huu}\Delta_H \bar{u}u$, where g_{Huu} is the Higgs boson coupling to a fermion represented by spinor u and Δ_H is the Feynman propagator of the Higgs boson.
- `SUBROUTINE fsfa` – returns matrix elements $g_{Suu}\Delta_S(\xi)\bar{u}u$, where $g_{Su_1u_2}$ is the scalar boson coupling to fermions represented by spinors u_1, u_2 and $\Delta_S(\xi)$ is the Feynman propagator of a scalar boson in an arbitrary linear gauge.
- `SUBROUTINE fsf` – returns the same as `fsfa` in the unitary gauge.
- `SUBROUTINE fvfa` – returns a set of four vectors of the form $\bar{u}_1\gamma_\nu(g_V^{(-)}P_- + g_V^{(+)}P_+) \times u_2 D_V^{\nu\mu}(\xi)$, where u_1, u_2 are fermion spinors, $P_\pm = (1 \pm \gamma_5)/2$, are chirality projectors, $g_V^{(\pm)}$ are the gauge boson-fermion couplings of definite chirality and $D_V^{\nu\mu}(\xi)$ is the propagator of a gauge boson V in arbitrary linear gauge.
- `SUBROUTINE fvf` – returns the same as `fvfa` in the unitary gauge.
- `MODULE gaugepar` – contains driving flags and gauge parameters for calculations in arbitrary linear gauge.
- `MODULE genpv12` – contains matrix elements representing the photon and Z boson coupling to initial state fermions.
- `MODULE genpv12g` – contains matrix elements representing the photon and Z boson coupling to initial state fermions including photon radiation from initial lines.
- `MODULE helproc` – contains numbers of possible helicity states of external particles.
- `SUBROUTINE inipart` – calculates content of modules `genpv12` and `genpv12g`.
- `MODULE inprms` – contains initial input parameters.
- `FUNCTION iomega` – calculates the soft bremsstrahlung phase space integrals as defined in Eq. (44) of [4].
- `SUBROUTINE kineeff1` – returns the four momenta, phase space normalization and flux factor for a $2 \to 2$ process in the CMS. The phase space is parametrized according to Eq. (9).

- SUBROUTINE `kineeffff` – returns the four momenta, phase space normalization and flux factor for a $2 \to 4$ process in the CMS. The phase space is parametrized according to Eq. (7) or (8), dependent on selected options.
- SUBROUTINE `kineeffffg` – returns the same as `kineeffff` for a $2 \to 5$ process in the CMS. The phase space is parametrized according to Eq. (10), (11) or (12), dependent on selected options.
- SUBROUTINE `kineetbff` – returns the same as `kineeffff` with the phase space parametrized according to Eq. (8).
- SUBROUTINE `kineetbffg` – returns the same as `kineeffff` with the phase space parametrized according to Eq. (11).
- SUBROUTINE `kinff` – returns the final state four momenta and phase space normalization for a $2 \to 2$ process in the CMS.
- SUBROUTINE `kinffg` – returns the same as `kinff` for a $2 \to 3$ process in the CMS.
- FUNCTION `lamsq` – the kinematic lambda function, $\lambda(\sqrt{x}, \sqrt{y}, \sqrt{z})$.
- SUBROUTINE `mateeee` – returns polarized matrix elements of $e^+e^- \to e^-e^+e^-e^+$.
- SUBROUTINE `mateeeeg` – returns polarized matrix elements of $e^+e^- \to e^-e^+e^-e^+\gamma$.
- MODULE `mathprms` – contains necessary arithmetical constants.
- SUBROUTINE `matllll` – returns polarized matrix elements of $e^+e^- \to l\bar{l}l\bar{l}$.
- SUBROUTINE `matllllg` – returns polarized matrix elements of $e^+e^- \to l\bar{l}l\bar{l}\gamma$.
- SUBROUTINE `matnnnn` – returns polarized matrix elements of $e^+e^- \to \nu_e\bar{\nu}_e\nu_e\bar{\nu}_e$.
- SUBROUTINE `matnnnng` – returns polarized matrix elements of $e^+e^- \to \nu_e\bar{\nu}_e\nu_e\bar{\nu}_e\gamma$.
- SUBROUTINE `matqqqq` – returns polarized matrix elements of $e^+e^- \to q\bar{q}q\bar{q}$.
- SUBROUTINE `matqqqqg` – returns polarized matrix elements of $e^+e^- \to q\bar{q}q\bar{q}\gamma$.
- MODULE `parproc` – contains parameters of a specific process.
- MODULE `parsm` – contains SM couplings and squared masses.
- SUBROUTINE `parspec` – returns parameters of a specific process (1) and (2), calculates the top quark and Higgs boson width to the lowest order of SM, the branching ratios for the narrow width approximations; initializes weights for the Monte Carlo integration.
- SUBROUTINE `psneeffff` – returns a phase space normalization as that of `kineeffff` for a given set of external particle momenta.
- SUBROUTINE `psneeffffg` – returns a phase space normalization as that of `kineeffffg` for a given set of external particle momenta.
- SUBROUTINE `psneetbff` – returns a phase space normalization as that of `kineetbff` for a given set of external particle momenta.

- `SUBROUTINE psneetbffg` – returns a phase space normalization as that of `kineetbffg` for a given set of external particle momenta.
- `SUBROUTINE recpol` – returns real polarization vectors of a vector boson in the rectangular basis.
- `FUNCTIONS scc, src` and `srr` (contained in `dotprod.f`) – return the Minkowski dot product of two complex, real and complex, and two real four vectors.
- `SUBROUTINE spheric` – returns spherical components `ps` of a four vector p^μ, `ps`= $(|\mathbf{p}|, \cos\theta, \sin\theta, \cos\phi, \sin\phi)$, with θ and ϕ being a polar and azimuthal angles of momentum $\mathbf{p}$.
- `SUBROUTINE spinc` – returns the contractions: $p^0 I - \mathbf{p}\cdot\sigma$ and $p^0 I + \mathbf{p}\cdot\sigma$, where $p^\mu = (p^0, \mathbf{p})$ is a complex four vector, I is the 2×2 unit matrix and σ are the Pauli matrices.
- `SUBROUTINE spinornew` – returns helicity spinors in the Weyl representation.
- `SUBROUTINE spinr` – returns the same contractions as in `spinc` for a real four vector p^μ.
- `MODULE topapprox` – contains SM lowest order widths of the top quark in different approximations.
- `SUBROUTINE uep` – returns a set of spinors of the form $\bar{u}\not{\epsilon}(g_V^{(-)}P_- + g_V^{(+)}P_+)S_F$, where S_F is a Feynman propagator of an internal fermion and the remaining notation is the same as in `fvfa`.
- `SUBROUTINE usp` – returns a set of spinors: $\bar{u}(g_S^{(-)}P_- + g_S^{(+)}P_+)S_F$, where S_F is a Feynman propagator of an internal fermion and $g_S^\pm$ are complex chirality couplings of the scalar boson to the fermion represented by spinor u.
- `SUBROUTINE wwidth` – returns the partial width of the W-boson averaged over initial spins and summed over final spins, and colors for hadronic decay modes.

3.3 Run output

A sample of the listing of the test run output is given in Appendix A. It contains a specification of the process, information on the scheme choice, and values of the relevant physical parameters in the very beginning. If cuts have been imposed (`icut = 1`) then there comes information about specified cuts. Then, if `iscan = 1`, results of the initial scan and resulting weights for the actual run are printed. If calculated weights do not add up exactly to 1 the last weight is changed slightly in order to satisfy the normalization condition. This change is completely irrelevant numerically, but the message about it is printed. The final result for the total cross section is called `Integral`. Its value is printed together with the standard deviation and the actual number of calls used in the calculation. Finally, if `imc = 1` then information on events acceptance efficiency is given, that means a fraction of accepted weight 1 events. The same kind of output is printed for the soft (without initial scan) and hard bremsstrahlung for each value of the CMS energy. In the very end, all the calculated total cross sections together with the corresponding standard deviations are collected in the tabular form.

If the event generation option is switched on, i.e. `imc = 1`, then the corresponding number of unweighted events will be printed out as collections of final state particle four momenta in a separate file called `events.dat`. Whenever a maximum value of the cross section initially assigned in `ee4fg.f`, or found in the result of the initial scan is overflown a corresponding message informing about it is printed in `events.dat`. The result of integration is still valid, however, if the program is run as an event generator, it should be rerun. How to proceed in this situation will be described in the next section.

4 Use of the program

Up to now the program have been run only on Unix/Linux platforms. In order to run the program, the user should select a specific name of a `FORTRAN 90/95` compiler, desired options and the name of the output file in the `makefile`. The output file is called `test` at present. The program can be then compiled, linked and run by executing a single command

`make test`.

The results of the test run should reproduce those contained in files `test.1` and `events.dat.1`.

The program can be run as the MC event generator of unweighted events by selecting

`imc = 1`

in `ee4fg.f`. It is then recommended to run the program for a single CMS energy and to perform a scan with a relatively large number of calls, `nscan0` or `nscanh`. Attention should be paid to possible messages informing about updates of the maximum weight. In this case the program should be rerun, however, this time without the initial scan. The initial integration weights `aw0` or `aw` in `parspec.f` and the maximum weight `crmax` in `ee4fg.f` should be updated according to the results of the prior scan. At present the efficiency of events acceptance is relatively low. However, in view of a relatively fast performance of the program, this should not be a serious limitation for the user.

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Appendix

A Listing of test run output

```
------------------------------------------------------------------------
                    Approaching the process:
                      e+ e- -> u d  mu- vm
                with the program 'ee4fg v.  1.0' by
                        Karol Kolodziej
              University of Silesia Katowice, Poland
                   e-mail:  kolodzie@us.edu.pl
                              and
                        Fred Jegerlehner
                          DESY-Zeuthen
                        Zeuthen, Germany
                     e-mail:  fjeger@ifh.de
------------------------------------------------------------------------
```

```
Fixed width scheme
Unitary gauge (Feynman gauge for a photon)

External fermion masses:  e- u d  mu- vm
0.51099890E-03 0.50000000E-02 0.90000000E-02 0.10565836E+00 0.00000000E+00
and widths:
0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00

Intermediate boson masses and widths:  W, Gm_W, Z, Gm_Z
80.42300 2.11800 91.18760 2.49520


Higgs boson mass and width:  H, Gm_H
0.11500E+03 0.49656E-02

1/alpha0 = 137.0359998 1/alphaw = 132.5440123 alphas = 0.1172000
sw2̂ = ( 0.222162337027705, 0.000000000000000) G_mu = 0.116639E-04

Minimum photon energy E_cut = 0.100E+01 GeV

------------------------------------------------------------------------

CUTS IMPOSED:
Lepton-beam angle (deg):
9.9364 < Theta_lb < 170.0636 => |cos(Theta_lb)| < 0.98500000
Lepton-quark angle (deg):
Theta_lq > 0.0000 => cos(Theta_lq) < 1.00000000
Lepton energy:  E_l > 5.0000 GeV
Quark energy:  E_q > 0.0000 GeV
Quark invariant mass:  m(q,q') > 10.0000 GeV
Photon-beam angle (deg):
9.9364 < Theta_gb < 170.0636 => |cos(Theta_gb)| < 0.98500000
Photon-lepton angle (deg):
Theta_gl > 5.0000 => cos(Theta_gl) < 0.99619470
Photon-quark angle (deg):
Theta_gq > 5.0000 => cos(Theta_gq) < 0.99619470
Photon energy:  E_g > 1.0000 GeV

------------------------------------------------------------------------


                              E_cm = 500.000 GeV


------------------------------------------------------------------------

The Born cross section of e+ e- -> u d  mu- vm

------------------------------------------------------------------------

Results of the initial scan:
Kinematics Weight Integral St.dev.  No of calls
1 0.33333333E+00 0.15393686E+03 0.18274875E+02 2000
```

```
7 0.33333333E+00 0.98339710E+01 0.15561981E+01 2000
8 0.33333333E+00 0.95066458E+01 0.18364902E+01 2000
-------------------------------------------------------------------------------

Born scanned with 5812 calls = 0.17327747E+03
Weight 8 = 0.5486371447956593E-01 rescaled to 0.5486371447956595E-01
Calculating the Born cross section with the weights:
Kinematics Weight Total
1 0.88838355E+00 0.88838355E+00
7 0.56752738E-01 0.94513629E+00
8 0.54863714E-01 0.10000000E+01
-------------------------------------------------------------------------------

Final result:
Integral = 0.208844E+03 Standard dev.  = 0.46E+01 with 98205 calls
Efficiency of the event acceptance = 0.274E-02
-------------------------------------------------------------------------------


The soft bremsstrahlung cross section of e+ e- -> u d  mu- vm

-------------------------------------------------------------------------------

Calculating the soft bremsstrahlung with the weights:
Kinematics Weight Total
1 0.88838355E+00 0.88838355E+00
7 0.56752738E-01 0.94513629E+00
8 0.54863714E-01 0.10000000E+01
-------------------------------------------------------------------------------

Final result:
Integral = 0.275032E+03 Standard dev.  = 0.57E+01 with 98309 calls
-------------------------------------------------------------------------------


The hard bremsstrahlung cross section of e+ e- -> u d  mu- vm

-------------------------------------------------------------------------------

Results of the initial scan:
Kinematics Weight Integral St.dev.  No of calls
1 0.66666667E-01 0.68245262E+01 0.79937410E+00 2000
2 0.66666667E-01 0.59318446E+01 0.40637476E+00 2000
3 0.66666667E-01 0.16450753E+01 0.44224431E+00 2000
4 0.66666667E-01 0.12864292E+01 0.53640805E+00 2000
5 0.66666667E-01 0.30076571E+01 0.73294260E+00 2000
37 0.66666667E-01 0.60163398E+00 0.77938298E-01 2000
38 0.66666667E-01 0.10923961E+01 0.53100141E+00 2000
39 0.66666667E-01 0.96635944E-01 0.21275410E-01 2000
40 0.66666667E-01 0.39577921E-01 0.75902751E-02 2000
41 0.66666667E-01 0.16723681E+00 0.30119527E-01 2000
43 0.66666667E-01 0.50777564E+00 0.55733184E-01 2000
```

```
44 0.66666667E-01 0.37973672E+00 0.40700755E-01 2000
45 0.66666667E-01 0.20752557E+00 0.54157642E-01 2000
46 0.66666667E-01 0.21579596E+00 0.51579026E-01 2000
47 0.66666667E-01 0.33355482E+00 0.61092215E-01 2000
--------------------------------------------------------------------------------

Hard bremsstrahlung scanned with 16877 calls = 0.22337402E+02
Weight 47 = 0.1493256995266576E-01 rescaled to 0.1493256995266579E-01
Calculating the hard bremsstrahlung with the weights:
Kinematics Weight Total
1 0.30552014E+00 0.30552014E+00
2 0.26555661E+00 0.57107675E+00
3 0.73646673E-01 0.64472342E+00
4 0.57590816E-01 0.70231424E+00
5 0.13464668E+00 0.83696092E+00
37 0.26933928E-01 0.86389485E+00
38 0.48904348E-01 0.91279920E+00
39 0.43261944E-02 0.91712539E+00
40 0.17718229E-02 0.91889721E+00
41 0.74868515E-02 0.92638407E+00
43 0.22732081E-01 0.94911615E+00
44 0.17000040E-01 0.96611619E+00
45 0.92904974E-02 0.97540668E+00
46 0.96607455E-02 0.98506743E+00
47 0.14932570E-01 0.10000000E+01
--------------------------------------------------------------------------------

Final result:
Integral = 0.251213E+02 Standard dev.  = 0.88E+00 with 76274 calls
Efficiency of the event acceptance = 0.839E-03
--------------------------------------------------------------------------------


cs0 (fb) sd cssb (fb) sd cshb (fb) sd cs(s+h)
0.20884E+03 0.46E+01 0.27503E+03 0.57E+01 0.25121E+02 0.88E+00 0.3002E+03
Born cross sections:
ecm cs0 sd0 csapp sda 0.5000E+03 0.20884E+03 0.46E+01 0.00000E+00 0.00E+00
Bremsstrahlung cross sections:
ecm cssb sdsb cshb sdhb 0.5000E+03 0.27503E+03 0.57E+01 0.25121E+02 0.88E+00
```