EEWW: a generator for $e^+e^- \rightarrow W^+W^-$ including one-loop and leading photonic two-loop corrections

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Abstract

We describe a generator for the process $e^+e^- \rightarrow W^+W^-$ including all one-loop and leading log photonic two-loop contributions. It includes polarization of the beam and $W$ bosons, and the possibility to study the effect of anomalous couplings.
1 Introduction

The computation of the one loop $W$ pair production cross section in $e^+e^-$ collisions has been performed a long time ago \cite{1, 2, 3}. The effects of hard radiation have been added to the last two calculations \cite{4, 5}. These results agree at the order of $10^{-3}$ or better \cite{5}, except at high energies in the forward direction, which is probably attributable to numerical instabilities. With the advent of LEP II there is a need for an event generator for $W$ pair production at this level. We present here such a generator based on the computations of Ref. \cite{7}. It includes the full one-loop matrix element, leading logarithm two-loop initial state bremsstrahlung, polarization effects and anomalous couplings. The main limitation is that we assume the $W$ bosons to be stable particles. Work to remove this limitation is in progress. We nevertheless think that the present version is useful in several respects: it includes the interesting part of the full process $e^+e^-\rightarrow W^+W^-\rightarrow$ four fermions and thus allows to study what we may learn from $W$–pair production under idealized circumstances. The missing part only involves well known physics, namely, the decays via the well established charged current interaction. The decays thus just serve as polarization analyzers for the $W$’s. Since a full $O(\alpha)$ calculation of the observed process $e^+e^-\rightarrow$ four fermions is a major enterprise, we think it will be useful for tests of parts of more complete calculations.

We first recapitulate the construction of an event generator, then discuss the polarization, initial state collinear bremsstrahlung and anomalous couplings. In the appendices technical details about the installation and sample input and output are given.

2 Event generator

The event generator presented here is based on the calculations \cite{3, 5, 7}. These, however, have all been presented as total and differential cross sections, or cross sections with certain cuts in the photon energy and the angle between the photon momentum and the beam axis. In the present work we present an event generator, i.e., a program which will give configurations $W^+W^- (\gamma)$ with probability proportional to the contribution to the total cross section. This allows experimental studies to be done including arbitrary cuts and detector capabilities. In this section we describe how the conversion was performed.

The last step to an event generator is simple: if the cross section is written as an integral over a positive function $f(\vec{x})$, with $\vec{x}$ a point in a hypercube $0 < x_k < 1$, and $f_{\text{max}}$ the maximum value of the function in this hypercube, event

\footnote{After writing this article it has come to our attention that a similar effort has been reported before \cite{6}.}
generators are given by the representation of the cross section

$$\sigma = \int d\vec{x} f(\vec{x}) \approx \frac{1}{N} \sum_{i=1}^{N} f(\vec{x}_i) \approx \frac{f_{\text{max}}}{N} \sum_{i=1}^{N} \theta \left( \frac{f(\vec{x}_i)}{f_{\text{max}}} - r_i \right) , \quad (1)$$

where the $\vec{x}_i$ are random points in the hypercube and the $r_i$ random numbers between 0 and 1; $N$ is the number of function evaluations used. The first sum corresponds to a weighted event generator, the second one to a weight-one event generator — all events correspond to the same probability. Both options are incorporated in EEWW, the first using the adaptive Monte Carlo routines vegas [5], the second one using non-adaptive algorithms simplemc and axmc. Experimental cuts and efficiencies can now easily be incorporated in the sums as $\theta$-functions, possibly involving more random numbers. For parton-level calculations a weighted Monte Carlo is generally more efficient, as the main cost is the evaluation of the matrix element. When a detector simulation is included, however, this part will take much more time, so a weight-one generator is generally used. The efficiency of the weight-one generator is given by

$$\epsilon = \int d\vec{x} \frac{f(\vec{x})}{f_{\text{max}}} \approx \frac{1}{N} \sum_{i=1}^{N} \theta \left( \frac{f(\vec{x}_i)}{f_{\text{max}}} - r_i \right) , \quad (2)$$

i.e., the average number of events generated per function evaluation.

The maximum value of $f(\vec{x})$ may not be known beforehand. We obtain an estimate by sampling the function at $10^{1+n/6}$ points for an $n$-dimensional function, and taking 20% more than the largest value found. This is adequate for a reasonably flat function. If during the generation a function value is found which is larger than the assumed maximum value, Eq. (1) is adjusted as

$$\theta \left( \frac{f(\vec{x}_i)}{f_{\text{max}}} - r_i \right) \rightarrow \text{int} \left( \frac{f(\vec{x}_i)}{f_{\text{max}}} \right) + \theta \left( \frac{f(\vec{x}_i)}{f_{\text{max}}} - \text{int} \left( \frac{f(\vec{x}_i)}{f_{\text{max}}} \right) - r_i \right) , \quad (3)$$

where int($x$) denotes the largest integer smaller than $x$. This means that the event is accepted as many times as is necessary to obtain the correct integral. As a result, not all events are independent, and statistical fluctuations may be larger than expected. Note that $f_{\text{max}}$ is not readjusted to reflect the new maximum found.

For our purpose we need to write the one loop cross section as an integral over a positive function on a hypercube. The hard radiation is already in this form:

$$\sigma^H_{1} = \frac{1}{2s} \int_{0}^{2\pi} d\phi_W \int_{-1}^{+1} d\cos\theta_W \int_{k_0 E_e}^{k_\text{max} E_e} E_\gamma dE_\gamma \int_{-1}^{+1} d\cos\theta_\gamma J |\mathcal{M}_1^H|^2 , \quad (4)$$

with $J$ the Jacobian defined in Ref. [3] and $E_\gamma$ the beam energy $E_e = \sqrt{s}/2$. $k_0$ is the minimum fraction of the beam energy the photon is allowed to have.
The mappings from the $x_i$ to the variables in Eq. (4) are also described in this reference; these map away the infrared $1/E_\gamma$, the collinear $1/(E_\pm p_\pm \cos \theta_\gamma)$, and the $t$-channel $1/t$ peaks of the matrix element squared.

The Born, virtual and soft contributions to the total cross section have the same form without photon integrals, so the integral can be taken the same with a flat behaviour in these dimensions. These two integrals are combined by introducing an extra (sixth) integration variable

$$
\sigma = \sigma_0 + \sigma_1^{V+S} + \sigma_1^H = \int_0^1 dx_6 \left\{ \frac{\theta(a - x_6)}{a} \left( \sigma_0 + \sigma_1^{V+S} \right) + \frac{\theta(x_6 - a)}{1 - a} \sigma_1^H \right\},
$$

(5)

with $0 < a < 1$ a tunable parameter. The distinction between hard and soft radiation is arbitrary; the only demand is that the cutoff $k_0$ is much smaller than unity to validate the eikonal approximation used in the soft bremsstrahlung integrals. We use this freedom to make the first term as small as possible without making it negative; a suitable choice is

$$
k_0 = \frac{\sqrt{s} - A}{B} \exp\left(-\frac{\pi}{2\alpha} - \frac{\pi^2}{6} + 1 - \frac{3}{4} \log(m_e^2/s)\right) - 1.
$$

(6)

The parameters $A = 130$ GeV, $B = 35$ GeV in the $\alpha$ scheme ($B = 9$ GeV in the $G_\mu$ scheme) and $a = \sqrt{s}/1000$ GeV below $\sqrt{s} = 350$ GeV, $a = 0.35$ above have been found by trial and error. At LEP II energies this gives $(\sigma_0 + \sigma_1^{V+S})/\sigma_1^H \sim 1/7$. As the virtual matrix element takes much longer to evaluate than the bremsstrahlung amplitude it is advantageous to keep this ratio as small as possible. Using these values we obtain a reasonably flat function $f(\vec{x})$. The efficiency, without any cuts, is about 40%. This translates to about 5 events per second on a workstation.

Note that the resulting soft photon spectrum, which seems to continue down to below 1 MeV, can not be trusted below a few times the $W$ width because of the narrow width approximation.

### 3 Polarization

Building on the calculations presented in Ref. [4] the event generator has many possibilities for studying the effect of different polarizations of the initial and final state.

The state of the beam is characterized by the electron and positron density matrices in the helicity frame

$$\rho_- = \frac{1 + \vec{\sigma} \cdot \vec{\tilde{P}}}{2} = \begin{pmatrix} 1 + P_L & P_T e^{-i\phi} \\ P_T e^{i\phi} & 1 - P_L \end{pmatrix},
$$

(7)

$$\rho_+ = \frac{1 + \vec{\sigma} \cdot \vec{\tilde{P}}'}{2} = \begin{pmatrix} 1 + P_L' & P_T' e^{-i\phi'} \\ P_T' e^{i\phi'} & 1 - P_L' \end{pmatrix}.
$$

(8)
where \( \vec{P} = (P_T \cos \phi, P_T \sin \phi, P_L) \), \( P_L \) is the longitudinal polarization and \( P_T \) the magnitude of the transverse polarization of the electron; \( P'_L, P'_T \) of the positron. The polarization vector of the electron (positron) is pointed in a direction \( \phi (\phi') \) upwards (downwards) from the outward direction. For the natural polarization in a storage ring \( \phi = \phi' = 90^\circ \). Special cases are no polarization \( (P_L = P_T = 0) \) and longitudinal polarization \( (P_T = P'_T = 0, P_L = \pm 1, P'_L = 0) \) for right- and left-handed polarization; these can be chosen separately. In the limit that the electron is taken massless the amplitudes for like-handed electrons and positrons \( (P_L = P'_L) \) are zero. The matrix element is then given by

\[
|M|^2 = \frac{1}{4} \left[ (1 - P_T P'_T)(|M_+|^2 + |M_-|^2) + (P_L - P'_L)(|M_+|^2 - |M_-|^2) + 2P_T P'_T \left( \cos(\phi - \phi' - 2\phi_W) \text{Re}(M_+ M'_-^*) + \sin(\phi - \phi' - 2\phi_W) \text{Im}(M_+ M'_-^*) \right) \right].
\]

A detailed discussion of the effect of the choices is given in Ref. [7].

The \( W \) bosons can have three polarization states: 2 transverse and 1 longitudinal. One can either choose to average over these in the matrix element (‘unpolarized’ \( W \)’s), or generate them separately (‘polarized’). In the latter case the polarization vector is made available, so that the subsequent decay of the \( W \) can take this information into account. The other two possibilities are to generate only longitudinal or transverse \( W^\pm \) bosons.

The generation of different polarization states is implemented by converting the sum over final states into an integral as

\[
\sum_{\lambda^+, \lambda^-} \sigma(\lambda^+, \lambda^-) = \int_0^1 dx \sum_{i=0}^8 \frac{\theta(x - c_i)\theta(c_{i+1} - x)}{c_{i+1} - c_i} \sigma(\lambda^+_i, \lambda^-_i),
\]

with \( \lambda^+_i = \text{int}(i/3) - 1, \lambda^-_i = \text{mod}(i, 3) - 1 \). The cutoff values \( c_i \) are chosen according to the lowest order matrix element squared at the same \( W^- \) angle:

\[
c_{i+1} - c_i = \frac{|M_0(\lambda^+_i, \lambda^-_i)|^2}{\sum_{j=0}^\infty |M_0(\lambda^+_j, \lambda^-_j)|^2}.
\]

The integration variable to make the discrete choice (10) is taken to be the rescaled version of the one used for the choice between the hard and other corrections (5).

\[4\] Initial state collinear bremsstrahlung

The largest corrections in the one-loop calculation are caused by initial state collinear bremsstrahlung. It is therefore natural to seek a way to include these.
to higher order. The leading log terms are well known \[9\]. They were included in Ref. \[5\] by replacing the lowest order term $\sigma_0(s)$ by

$$\sigma^{\text{ini}}(s) = \int_0^{k_{\text{max}}} dk \, \rho_{\text{ini}}(k) \sigma_0(s(1-k)),$$

(12)

with the function $\rho_{\text{ini}}$ given by

$$\rho_{\text{ini}}(k) = \beta k^{\beta-1} \left( 1 + \delta_1^{V+S} + \delta_2^{V+S} \right) + \delta_1^H + \delta_2^H,$$

(13)

with $\beta = 2\alpha/\pi(L-1)$ and $L = \log(s/m_e^2)$ the large collinear logarithm. The terms $\delta$ denote the infrared finite parts of the leading one- and two-loop corrections. Explicit expressions are given in Refs \[9, 5\], except that we use $\delta_1^H = \alpha/\pi((L-1)(k-2) + k)$, which differs by the last (non-leading) term.\[4\] However, one has now included the one-loop leading corrections twice; this is corrected for by subtracting the unexponentiated $O(\alpha)$ contribution from this formula:

$$\sigma^{\text{double}} = \left( \beta \log k_0 + \delta_1^{V+S} \right) \sigma_0(s) + \int_{k_0}^{k_{\text{max}}} dk \left( \frac{\beta}{k} + \delta_1^H \right) \sigma_0(s(1-k)),$$

(14)

with $k_0$ an arbitrary (small) cutoff.

This procedure, however, is not suited for an event generator. First, a separate structure function has to be assigned to each incoming particle \[10, 11, 12, 13\]; these are identical to $\rho_{\text{ini}}$ with $\beta \rightarrow \beta/2$; for simplicity we will keep the single integral notation. A more subtle point is that the structure function \[13\] has been computed by solving QED evolution equations after integrating out the angles of the extra photon over all phase space. This inclusive approach is not appropriate for an event generator. We solve this by dividing phase space into two regions: inside a cone of opening angle $\theta_c$ around the beam direction one declares all photons collinear (and makes an inclusive measurement), outside it one measures the angles (and measures exclusively). Only in the phase space inside this cone ($\theta_c$ is assumed to be much larger than $m_e^2/s$) we use the exponentiated two-loop structure function. Outside this cone the $O(\alpha)$ result is used, with the possibility of extra collinear photons. The two limiting cases are $\theta_c = 0$, which gives a strict $O(\alpha)$ behaviour, and $\theta_c = \pi$, which reproduces the totally integrated cross section computed before.\[5\] Integrating only over the angles inside the cone amounts to replacing $s$ by a scale $\mu^2 = s(1 - \cos \theta_c)/2$ in the collinear large logarithms: $L = \log(\mu^2/m_e^2)$. A calculation of the $p_T$ dependence of the structure functions has not been done yet and is beyond the scope of this article.

A technical problem is that adding and subtracting parts does not give the positive definite integrand needed for an event generator. To obtain this we

\[3\]Numerically, the difference is less than 0.1%.

\[4\]The region $\pi/2 \leq \theta_c < \pi$ is redundant from an experimentalists’ point of view, but the collinear terms have to be integrated over all angles to obtain the full result.
rewrite the total cross section as
\[ \sigma = \sigma_{\text{ini}} + \sigma_{\text{V+S}}^1 - \sigma_{\text{double}} \]
\[ = \int_{k_0}^{k_{\text{max}}} dk \rho_{\text{ini}}(k) \sigma_0(s(1-k)) + \left[ \sigma_{\text{V+S}}^1(s) - \left( \beta \log k_0 + \delta_{\text{V+S}}^1 \right) \sigma_0(s) \right] \]
\[+ \left[ \sigma_{H}^1(s) - \int_{k_0}^{k_{\text{max}}} dk \left( \frac{\beta}{k} + \delta_{H}^1 \right) \sigma_0(s(1-k)) \right]. \] (15)

The terms in square brackets are of order \( \alpha \) and do not contain any large collinear logarithms; we can therefore add them to the first integral without introducing terms of order \( \alpha^2 L \):
\[ \sigma = \int_{k_0}^{k_{\text{max}}} dk \rho_{\text{ini}}(k) \left( \sigma_0 + \tilde{\sigma}_{\text{V+S}}^1 + \tilde{\sigma}_{H}^1 \right)(s(1-k)), \] (16)

with \( \tilde{\sigma}_i \) the differences in square brackets in Eq. (15). The virtual and soft one is easily computed, to subtract the leading log from the hard radiation we have to reintroduce the \( \cos \theta \) integral as (see, e.g., [14])
\[ \int_{k_0}^{k_{\text{max}}} dk \frac{\beta}{k} = \frac{\alpha}{\pi} \int_{k_0}^{E_{\gamma}} dE_{\gamma} \left( \int_{-1}^{1} \frac{d \cos \theta_e}{E_e + p_e \cos \theta_e} \frac{p_e}{E_e + p_e \cos \theta_e} + \int_{1}^{1} d \cos \theta_e \frac{p_e}{E_e - p_e \cos \theta_e} \right) \] (17)

This can be subtracted from the hard radiative integral over a 3-particle phase space if one adds a \( \phi \) integral (which is trivial for \( P_T = 0 \), otherwise the same \( \phi \)-dependence is taken as the lowest order). A similar approach is followed for the double pole terms; here the upper integration boundary is of order \( m_e^2/s(1-\cos \theta_e) \) which can be neglected when \( \theta_e \ll m_e^2/s \). The final result is just the collinear limit used already in Refs [13, 3], but now applied for all angles up to \( \theta_e \) in both the forward and backward direction.

Unfortunately there is no reason for the integrand of \( \tilde{\sigma}_{H}^1 \) to be positive definite; indeed, in the collinear limit it is zero. Recalling that within the collinear cone we do not make a distinction between different collinear photons we add a fraction of the Born cross section to restore positivity. We take
\[ \tilde{\sigma}_{H}^1 = \sigma_{H}^1 - \frac{\alpha}{\pi} \int_{k_0}^{k_{\text{max}}} dk \left( \int_{-1}^{1} \frac{d \cos \theta_e}{E_e + p_e \cos \theta_e} \frac{p_e}{E_e + p_e \cos \theta_e} + \int_{1}^{1} d \cos \theta_e \frac{p_e}{E_e - p_e \cos \theta_e} \right) \]
\[ \times \left[ \frac{1}{k} d \sigma_0((1-k)s) - \frac{d \sigma_0(s)}{d \cos \theta} \right] \] (18)
\[ \tilde{\sigma}_{V+S}^1 = \sigma_{V+S}^1 - \frac{\alpha}{\pi} \left( 2(L-1) \log k_{\text{max}} + \left( \frac{3}{2} - 2k_{\text{max}} \right) L + \frac{\pi^2}{3} - 2 + 2k_{\text{max}} + \frac{1}{2} k_{\text{max}}^2 \right) \sigma_0(s) \] (19)

where \( p_\pm \) is the positron (electron) momentum in the first (second) \( \cos \theta \)-integral. Note that \( k_{\text{max}} \) depends on the angle between the \( W^- \) and the incoming electron. As the expression for the hard bremsstrahlung is dominated by the added Born term we generate an event with only collinear photons in this region.
5 Anomalous couplings of the $W$ boson

One of the main purposes of LEP II being the study of the $WW\gamma$ and $WWZ$ interactions we allow for the inclusion of non-standard couplings at these vertices $^{[10, 17]}$. We parametrize these by the CP-invariant effective interaction Lagrangean for the $WWV$ interaction ($V = \gamma$ or $Z$)

$$\mathcal{L}_{SM}^V = iC_V \left\{ V^\nu (W^\pm_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^+_{\mu}) + V^{\mu\nu} W^+_{\mu} W^-_{\nu} \right\} \tag{20}$$

$$\Delta \mathcal{L}_{\text{eff}}^V = iC_V \delta_V \left\{ V^\nu (W^+_{\mu\nu} W^-_{\mu} - W^-_{\mu\nu} W^+_{\mu}) + V^{\mu\nu} W^+_{\mu} W^-_{\nu} \right\} + iC_V \delta\kappa_V V^{\mu\nu} W^+_{\mu} W^-_{\nu} + iC_V \frac{\lambda^V}{m_W^2} V^{\mu\nu} W^{+\rho\nu} W^-_{\rho\mu} + C_V \xi_V \left( \partial^\rho \tilde{V}^{\nu\rho} \right) \left\{ W^+_{\mu} \partial^\rho W^-_{\nu} + W^-_{\mu} \partial^\rho W^+_{\nu} \right\} \tag{21}$$

Electromagnetic gauge invariance forces $\delta_\gamma = 0$. This effective Lagrangean is related to the other widely used form $^{[18]}$ by $g_1^V = 1 + \delta_V$, $\kappa_V = 1 + \delta_V + \delta\kappa_V$ and $f_5^V = \xi_V s/m_W^2$. Whereas CP-violating terms are known to be small, we see no reason to neglect the parity-violating form factors $\xi_V$.

The inclusion of these anomalous couplings in a one-loop expression causes problems, as the resulting theory is non-renormalizable. We assume that the anomalous couplings are small perturbations of the standard model, and that the leading effects enter only in the Born term. They are therefore not included in the $\mathcal{O}(\alpha)$ corrections, in particular not in the hard (non-collinear) bremsstrahlung. The usage of a different expression for the Born term in the soft bremsstrahlung will upset the validity of Eq. (3) which assures the positivity of the integrand. This only causes negative events when the anomalous couplings decrease the Born matrix element squared, which, due to the violation of the gauge cancellations, happens only in the backward direction ($\cos\theta_W \approx -1$). We therefore increase the cutoff by a factor $1/x_5^2$, where $x_5$ is the random variable which is mapped to $\cos\theta_W$. In case of problems one can rescale $k_0$ by an arbitrary factor. At high energies, for large anomalous couplings and with extra initial state collinear radiation it may not be possible to avoid negative points.

6 Anomalous couplings and loop effects

We have compared the effects of anomalous couplings of the $WWZ$ vertex to the one-loop corrections in the total cross section and the angle of the $W^-$ boson. One should note that the effects of the one-loop corrections is to entirely different amplitudes than those affected by anomalous couplings. The effective one-loop contributions to the anomalous couplings defined in Eq. (21) are of order $\alpha/\pi$, i.e., a few times $10^{-3}$. This is completely negligible at the precision expected at LEP II. The large one-loop contributions therefore originate in different form factors, like the ones associated with the $t$-channel graphs. These also affect simple distributions like $d\sigma/d\cos\theta_W$. 


The values used for the parameters were $m_Z = 91.176$ GeV, $m_W = 80.152$ GeV, $m_t = 174$ GeV, $m_H = 100$ GeV. We assumed unpolarized beams of 87 GeV each and used the $G_\mu$ renormalization scheme. The results are shown in Fig. [1]. One sees that the main effect of the radiative corrections is described fairly well by a structure function in a cone of $10^\circ$. However, the difference is still of the same order of magnitude as the deviations caused by a variation of 0.1 in a single anomalous $WWZ$ coupling.

![Graph](image.png)

Figure 1: The effect on $\frac{d\sigma}{d\cos \theta_W}$ of one-loop corrections and anomalous couplings at $\sqrt{s} = 174$ GeV. Initial state radiation (in a cone of $10^\circ$) has been taken into account unless otherwise stated.

7 Summary

We have presented an event generator for $e^+e^- \rightarrow W^+W^-$ which includes

- full $\mathcal{O}(\alpha)$ corrections, including hard bremsstrahlung, both in the $\alpha$ as in the $G_\mu$ scheme,
- two-loop leading log effects for the initial state collinear bremsstrahlung,
- beam polarization (both transverse and longitudinal),
- polarization of the $W$’s,
- anomalous couplings of the triple gauge boson vertices.

It works in the energy range from threshold to 500 GeV (above this there are numerical instabilities, especially in the forward region). The generation speed is of the order of 5 points per second on a workstation. The main limitation is the lack of offshell effects; we are working on this problem.

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A Installation

The whole package has been written in Fortran 77 with some extensions and has been tested on Sun[1], DEC α, NeXT and HP[2] workstations. Due to the required range in floating point numbers, \((m_e/m_W)^2\), it does not run as is on non-IEEE computers like VAX[3] and IBM mainframes.

The program consists of the following parts:

- two main programs; one reads its data from a file eeww.dat and calls vegas or simplemc to generate the events as a stand-alone program; the other demonstrates the use of axmc, which can more easily be tied into standard libraries,

- the switchyard routine wmmc, corresponding to \(f(\vec{x})\) in Eq. (1), which calls virt or hard,

- the main routines with all the physics formulæ,

- the library axo.a, which contains the vegas[4], simplemc, axmc and supporting routines for integration and event generation,

- the tensor reduction library aa.a and

- the library of scalar functions ff.a[19, 20].

The whole package can be obtained with anonymous ftp from pss058.psi.ch in the subdirectory /pub/eeww.mc, or as a gzip’d tar file. The integration and event generation routines can easily be replaced by other packages.

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5 We had problems with the optimizer on Solaris
6 Do not use +O2, change xor to ieor in axo/ranf.f, line 498 and include flush.hp.o
7 One could use GFPLOAT, but this normally causes problems with libraries
B Usage

There are two ways to generate events. The program eeew reads its input data from a file eeew.dat, which it expects in the current directory. This file is read a line at a time, with optional lines being skipped over. An example file is shown below.

```
Standard  comment line
1  order to which the computation is done: 0 or 1
gmu  renormalization scheme: either 'alpha' or 'gmu'
91.176  mZ Z boson mass
80.152  mW W boson mass
130.0   mt top quark mass
100.0   mH Higgs boson mass
2     1d-3 IR: 0:normal cutoff, 1:Veltman, 2:computed, 3:rescale; cutoff/scale
2     10.  extra initial state coll. radiation: 0:not, 2:included; cone angle
polarized  electron polarization: unpolarized, lefthanded, righthanded, polarized
0. 0.   .9 90. 90.  if polarized, polarization matrix (plm,plp,ptm,ptp,fim,fip)
polarized  W- polarization: unpolarized, polarized, transverse or longitudinal
polarized  W+ polarization: unpolarized, polarized, transverse or longitudinal
standard  anomalous couplings?  standard or nonstandard.
   .1 .1 .1 .1 if nonstandard:  dkapg, lamg, xig
0 .1 .1 .1 if nonstandard:  d1z, dkapz, lamz, xiz
1     number of CMS energies
200.   CMS energies
simple  method: one of 'vegas' or 'simple'
1     simple: number of points points to generate
```

The other method, useful for connecting with other programs, is demonstrated by eeewax. This interface consists of an initialisation call, a call which generates exactly one event, and an exit routine. The parameters corresponding to the data file are passed as arguments.

The events are output in the routine wweven, which would be the point where the W’s are decayed and the event analyzed. A sample routine calling jetset [21] is included. It has access to arrays of four-momenta, polarization vectors and strings, and particle identification codes. Please refer to the comments in this files for details.

C Sample output

The output of the program with the demo routine wweve, given the input file reproduced above, is shown below. Please contact the authors if you have problems reproducing this or other problems.
An order(\alpha) generator for \textit{W} pair production in electron positron events. J. Fleischer, F. Jegerlehner, K. Kolodziej, G.J. van Oldenborgh=

\begin{verbatim}
FF, a package to evaluate one-loop integrals written by G. J. van Oldenborgh, NIKHEF-H, Amsterdam

for the algorithms used see preprint NIKHEF-H 89/17, 'New Algorithms for One-loop Integrals', by G.J. van Oldenborgh and J.A.M. Vermaseren, published in Zeitschrift fuer Physik C46(1990)425.

ffinit: precx = 4.408920985006D-16
ffinit: precx = 4.408920985006D-16
ffinit: xalogm = 4.9406564584125-324
ffinit: xclogm = 4.9406564584125-324

Standard comment line
eeww: order(\alpha) calculation
eeww: working in the Gmu scheme
eeww: using masses:
mZ = 91.176000000000
mW = 80.152000000000
mtop = 130.000000000000
mH = 100.000000000000
eeww: will compute the cutoff myself
eeww: including the 2-loop leading log hard and exponentiated soft photon effects in cones of 10.000000000000000 degrees around the beam directions
eeww: longitudinal polarization electron = 0.
   longitudinal polarization positron = 0.
   transverse polarization electron = 0.9000000000000000
   in direction 90.000000000000000000000 degrees
   longitudinal polarization positron = 0.9000000000000000
   in direction 90.000000000000000000000 degrees

NPOIN: warning: D4 is not yet supported
\end{verbatim}
NPOIN: warning: B1’ seems also not yet supported

ffxdbd: IR divergent B0’, using cutoff 1.0000000000000D-24

ffxdbd: using IR cutoff delta = lam^2 = 1.0000000000000D-24

ffxc0i: infra-red divergent threepoint function, working with a cutoff 1.0000000000000D-24

ffzdbd: using IR cutoff delta = lam^2 = 1.0000000000000D-24

maxweight increased to 37.140069173089 at event -212

maxweight increased to 37.296235986855 at event -4

simplemc: using as maximum weight: 44.755483184226

# id E px py pz eps_0 eps_x eps_y eps_z mass polarization
1 11 99.431 0.000 0.000 99.431 0.000 0.000 0.000 0.001 POLARIZED
2 -11 99.431 0.000 0.000 -99.431 0.000 0.000 0.000 0.001 POLARIZED
3 -24 99.117 19.937 2.770 54.723 0.000 -0.138 0.990 0.000 80.152 Y TRANSVERSE
4 24 99.748 -19.937 -2.770 -55.858 0.002 0.931 0.129 -0.342 80.152 X TRANSVERSE
6 22 1.135 0.000 0.000 1.135 0.000 0.000 0.000 0.000
7 22 0.001 0.000 0.000 -0.001 0.000 0.000 0.000 0.000

The Lund Monte Carlo - JETSET version 7.3
** Last date of change: 14 Jun 1991 **

cross section using weights = 18.732903091335
cross section using 0 or 1 = 44.755483184226
generated 1 points
acceptance rate = 100.0000 %
weight of each accepted event= 18.732903091335
eeww: energy = 200.00000000000 GeV
c.s. = 18.732903091335 +/- 18.732903091335
chi2 = 0./DOF

total number of errors and warnings
===================================

fferr: no errors