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HERACLES: an event generator for ep interactions at HERA energies including radiative processes

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A Monte Carlo event generator simulating neutral and charged current ep interactions at HERA energies and beyond is described. The present version 4.0 of the generator optionally treats the ep scattering either by means of structure-function parametrizations or on the basis of parton distribution functions in the framework of the quark–parton model. Single-photon emission from the lepton line as well as self-energy corrections and the complete set of one-loop weak corrections can be included. These corrections are sufficient to describe the cross-section with an accuracy of a few percent or, if $Q^2 \leq 2 \times 10^3$ GeV^2, of less than 1%.

PROGRAM SUMMARY

Title of program HERACLES 4.0

Catalogue number: ACGE

Program obtainable from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue)

Licensing provisions: none

Computer for which the program is designed and others on which it has been tested:
Computers: IBM-3090, VAX; *Installations*: DESY, Hamburg, Germany

Operating systems or monitors under which the program has been tested: VM-CMS, VAX-VMS

Programming language used: FORTRAN-77

No. of lines in distributed program, including test data, etc.: 11042

Other programs used: VEGAS [1], Multidimensional Monte Carlo integration; RNDM (), random number generator, method taken from ref. [2]; D01FCF, two-dimensional integration routine of a non-singular integrand with constant integration limits, taken from the NAGLIB library

Keywords: Monte Carlo event generator, ep reactions, radiative processes

Nature of physical problem
Simulating neutral and charged current ep interactions at HERA energies and beyond.

Method of solution
Monte Carlo event generating.

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Typical running time
Depending on the actual requirements (parameters, requested contributions, kinematical limits, initialization); typical example: 1000 radiative events/5 s. CPU. For a more detailed discussion see section 5 of the Long Write-Up.

References

[1] G.P. Lepage, J. Comput. Phys. 27 (1978) 192.
[2] G. Marsaglia and A. Zaman, Towards a universal random number generator, Florida State Univ. Preprint FSU-SCRI (1987). See also F. James, Comput. Phys. Commun. 60 (1990) 329.

LONG WRITE-UP

1. Introduction

In order to plan the HERA experiments it is necessary to have detailed information on the characteristics of events that are predicted by the standard theory. Higher-order electroweak effects not only change the amplitudes of the tree-graph process, but also introduce new types of events. On the one-loop level additional photons can emerge. The most flexible method to study these effects is the application of a Monte Carlo event generator which simulates an experiment by constructing events according to probabilities given by the appropriate differential cross-sections. These events are fully characterized by the quantum numbers, masses, and momenta of the final-state particles. Samples of generated events can then easily be used to perform simulations of possible measurements.

In this note we present a technical description of the event generator HERACLES, version 4.0, for the simulation of deep inelastic $e^{\pm}p$ collisions via the neutral-current as well as charged-current interactions at HERA energies. The first-order electroweak radiative corrections to deep inelastic scattering at HERA are known to be large, particularly for the neutral-current process in the low-x/high-y region [3,4]. They are mostly due to radiation of real and virtual photons from the lepton line (see fig. 1). These leptonic corrections together with the fermionic contributions to the photon and Z or W self-energies are sufficient to describe the differential cross-section $d^2\sigma/dx dy$ with an accuracy of better than 5% or, if x or y are not extremely large, i.e. if $Q^2 \leq 2 \times 10^3$ GeV^2, better than 1%. The event generator HERACLES includes the leptonic corrections as well as the complete one-loop virtual corrections using the results of ref. [3] and is thus able to give a good description of radiative effects at HERA.

The most important capabilities of the generator are:

- It allows integration of the differential cross-sections for $lp \rightarrow l'X$ and $lp \rightarrow l'\gamma X$ over kinematical regions which can be defined in terms of the variables x, y, Q^2. These kinematic variables are determined from the outgoing lepton's energy and scattering angle. As well, in the calculation of the

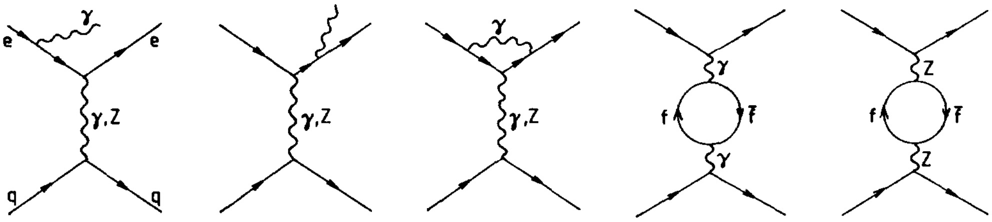

Fig. 1. Feynman diagrams describing the $\mathcal{O}(\alpha)$ leptonic corrections for neutral-current electron–quark scattering and the fermionic contributions to the photon and Z self energies.

cross-section for lp → l′γX it is possible to limit the phase space by requiring a minimal value for the photon energy E_γ.

- The program performs event generation in predefined kinematical regions, as in the integration step. The generated events are described by the 4-momenta of the final-state particles (electrons/ neutrinos, quarks, and photons) and the flavor of the scattered quark.
- The structure of the program allows a separate treatment of the Born term and several parts of the leptonic QED corrections (comprising soft- and hard-leptonic bremsstrahlung and the corresponding virtual corrections). These parts describe for the neutral-current reaction initial-state radiation, final-state radiation, and a contribution called Compton part. In the case of the charged-current reaction, there is only one radiative channel describing radiation from the initial lepton.
- Optionally, various parts of weak virtual corrections can be included (self-energies, vertex corrections, box diagrams).
- The program describes electron as well as positron scattering and allows for polarized leptons.
- The user can choose among a set of parametrizations for input parton distributions. The list of parametrizations may be easily extended by the user.

The present version 4.0 of HERACLES supersedes former versions in the following respects:

(1) HERACLES itself generates events at the parton level. However, the interface DJANGO is now available which calls routines from LEPTO 5.2 and JETSET 6.3 for the fragmentation and hadronization of the scattered quark and the proton remnant [5].
(2) The charged current process is now included.
(3) It is also possible to use arbitrary structure functions to describe the electron–proton cross-section without relying on the parton model. In particular, a non-zero longitudinal structure function F_L can be included. Note that in this case it is not reasonable to perform the hadronization step, because the prescriptions realized in LEPTO 5.2 are based on the parton model.
(4) The kinematic range where the program is applicable has been increased: After restoring terms proportional to the electron and the proton masses, the program agrees now with ref. [4] also for very small x down to $x = 10^{-4}$ and large y up to $y = 0.99$.

Moreover, a uniform naming of functions, subroutines and common blocks has been introduced in order to avoid confusion when interfacing HERACLES with other program packages. In version 4.0 all names start with the two letters HS except those for subroutines that were taken from elsewhere (e.g. VEGAS, PYSTFU and the random number generator RNDM which the user will probably wish to exchange anyway).

Since exponentiation of soft-photonic corrections is not yet included, the program is still restricted to not too small values of y and not too large x. In the present version x and y must lie in the region

$$y(1-x)^2 \geq 0.004.$$

Considering the kinematical region accessible for HERA experiments [6], this condition does probably not limit the applicability of the generator. The limitation to $Q^2 \geq 4$ GeV^2 of former versions has now been removed. The user has to make sure by himself that parametrizations for structure functions are used which are valid in the whole kinematic region considered.

We want to stress again that the present version of HERACLES is able to describe the differential cross-section for scattering of polarized electrons and positrons well with an accuracy of better than 5% for not too extremely large values of x and y. This is completely sufficient for the data analysis during the first one or two years of experimentation at HERA. In the long run, however, the measurement of charge and polarization asymmetries will probably be possible with a higher precision. These observables receive non-negligible corrections from $\gamma\gamma$ boxes and the interference of leptonic and quarkonic radiation and, therefore, cannot be described with a sufficient accuracy by the present version of the program. For these reasons there is a continuing effort to remove these limitations in future releases of the generator.

In section 2 we describe shortly the physics that is simulated by HERACLES and in section 3 some technical details. In section 4 we explain how to use the program, what kind of input is expected, and how the user can extract the desired information on generated events. Finally, in section 5 we report some first experience with the program. Further details are given in several appendices. First results from HERACLES have been published in ref. [7].

2. Treatment of physics input

HERACLES has two choices for the description of deep inelastic scattering of electrons or positrons off protons.

The first possibility is based on a model-independent formulation of the ep cross-section in terms of arbitrary structure functions F_1, F_2 and F_3. This description is suited for electron-inclusive measurements. Events generated by using this option contain the 4-momentum of the outgoing lepton (and photon in case of radiative events) and the total 4-momentum of the hadronic final state. If this structure-functions option is used, only leptonic QED corrections and self-energies of the exchange bosons can be included.

The second choice is based on the parton model where the lepton–proton cross-section is determined from hard lepton–quark scattering processes. In the following we focus our description on this option.

The underlying cross-sections [3,4] for $\mathrm{lq} \to \mathrm{l'q}$ (elastic scattering) and for $\mathrm{lq} \to \mathrm{l'q}\gamma$ (bremsstrahlung) contain the standard electroweak interaction mediated by photon and Z or W exchange. The dependence on the lepton polarization is also included, although a specific helicity state is not assigned to individual events. For each event the actual quark flavor is sampled according to the relative magnitude of the contributions from individual flavors to the differential cross-section. The flavor content in the total event sample thus depends on the kinematical region considered, as well as on the choice of the quark distribution functions. These distribution functions may be Q^2 dependent and thus include leading-logarithmic QCD corrections. Other $\mathcal{O}(\alpha_s)$ corrections (e.g. the longitudinal structure function) are not included, however.

Several switches allow to include the $\mathcal{O}(\alpha)$ electroweak virtual corrections (self-energies, vertex corrections, and box diagrams) into the non-radiative cross-section. If only a moderate accuracy is required one can turn off the weak contributions saving thereby a considerable amount of CPU time. There is also a switch that determines whether the electroweak parameters are calculated from fixed Z and W boson masses M_Z, M_W or from fixed M_Z and the μ decay constant G_μ.

The bremsstrahlung cross-section is split into a soft and a hard part. The soft-bremsstrahlung is treated analytically and included as a correction in the non-radiative cross-section. It describes emission of photons with an energy smaller than a cutoff E_γ^{soft}. This cutoff depends on x and y and is chosen by the program such that it is small as compared to the threshold of photon detection. The user has no access to this quantity unless a hard-photon cut is requested. In this case integration or sampling includes only the radiative contributions, E_γ^{soft} is taken from the user input and has the meaning of the minimal energy of emitted photons. E_γ^{soft} is defined in the HERA-laboratory reference frame.

The hard-bremsstrahlung contribution describes events with a resolved photon. These events are described by the Lorentz-invariant variables

$$s=(p+q)^2, \qquad t=(p-p')^2, \qquad u=(p'-q)^2,$$
$$s'=(p'+q')^2, \qquad t'=(q-q')^2, \qquad u'=(p-q')^2,$$

where $p(p')$ and $q(q')$ denote the 4-momenta of the incoming (outgoing) leptons and quarks, respectively. We use also the 4-products of the fermion momenta with the photon-momentum k and the "true" scaling variable x',

$$x' = \frac{-(p-p'-k)^2}{2P(p-p'-k)}.$$

Internally, the following integration variables are used: x, $Q^2 = -t$, x', $-t'$, and one of the invariants kp or kp' (depending on the channel). For the neutral-current process, the hard bremsstrahlung is split into three contributions. Two of them correspond to the collinear peaks from initial- and final-state leptonic radiation. The third one is dominated by the kinematical situation where the electron scatters off an almost real photon, collinear to the incident quark (Compton contribution). For the charged-current reaction there is only one channel describing radiation from the initial-state electron. These parts may be used separately. Each of these contributions gives a very good approximation for the spectrum of emitted photons in the corresponding phase-space region but all of them are needed to obtain a reasonable prediction for the photon-inclusive cross-section.

Further details of the treatment of the bremsstrahlung contributions, like explicit cross-section formulas, choice of variables and kinematical limits are given in refs. [7,8].

3. Sampling techniques

The computational procedures applied in HERACLES are based on the methods used in the AXO library [9] for Monte Carlo integration and event generation. AXO itself relies on the Monte Carlo integration algorithm VEGAS by P. Lepage [1]. The method may be characterized as a combination of adaptive importance sampling [1] and an optimized von-Neumann rejection technique [9].

According to this procedure, the following steps have to be performed in actual computations:

1. Integration of the different contributions to be included. Thereby partial cross-sections are determined according to the actually defined phase-space region. They define the relative weight of the corresponding contribution in the final step of event sampling. Furthermore, the integration procedure supplies information for the construction of the distribution function applied for event generation.
2. Estimation of the local maxima of the distribution function in a predefined number of hypercubes, since the integration volume is subdivided to optimize the rejection procedure. This step is usually executed together with the integration step 1.
3. Event sampling. According to the partial cross-sections determined in step 1, events are generated randomly from the individual contributions (Born term including soft and virtual corrections, initial- and final-state leptonic radiation, and Compton part, respectively).

Note that steps 1 and 2 are necessary for each individual contribution to be included in the event generation. For flexibility (in particular with respect to CPU-time requirements) and test purposes, the program allows a treatment of the different steps for each contribution separately. The information obtained in steps 1 and 2 is always written to an external file which has to be assigned in the corresponding run. If step 3 is done in a separate run of the program, a corresponding file had to be prepared in a preceeding run which performed at least steps 1 and 2. The random number seeds for refined integration by VEGAS or continued event sampling can also be stored on an external file. Conventions for file units are defined in the next section.

4. Technical description

4.1. Input to the program

The input to the program has the following general structure: an option card defining the expected information (FORMAT (A10)) is to be followed by one card containing the appropriate data (format-free). In general, the sequence of different options does not matter, only the START option (see below) triggering the actual operation of the program has to be the last one.

In the following we describe the potential input options and the corresponding data expected by the program. Default values are given in brackets.

TITLE
data: user defined heading of the first page.

EL-BEAM
data: EELE, POLARI, LLEPT;
quantities defining the properties of the electron beam.
EELE = energy of the electron beam in GeV (30 GeV);
POLARI = degree of beam polarization (0.0), $-1 \leq$ POLARI ≤ 1;
LLEPT = lepton charge (-1),
= -1, electron beam,
= $+1$, positron beam.

PR-BEAM
data: EPRO;
properties of the proton beam.
EPRO = energy of the proton beam in GeV (820 GeV).

KINEM-CUTS
data: ICUT, XMIN, XMAX, YMIN, YMAX, Q2MIN, WMIN;
definition of kinematical cuts to be applied.
ICUT = 1: cuts in x and lower cut in Q^2 (Q2MIN in GeV^2), cuts in y are ignored,
= 2: cuts in x, lower cut in Q^2 and lower cut in the hadronic mass W (WMIN in GeV), cuts in y are ignored,
= 3: cuts in x, y, Q^2 and W.
Default: ICUT = 3. The final definition of cuts according to the most restrictive conditions is performed in the subroutine HSPRLG; details are given in appendix A.

EGAM-MIN
data: EGMIN;
definition of a lower cutoff energy for bremsstrahlung photons (in GeV).
EGMIN = 0.0: Integration and/or simulation of both radiative and non-radiative events (default). Internally a value for the minimal photon energy in radiative events is calculated depending on x and y. This option should be used only if integration/sampling of the non-radiative channel is also requested by setting INC2 (ICC2) = 1 and/or ISNC2 (ISCC2) = 1 or 2.

EGMIN > 0.0: Only hard-photon bremsstrahlung considered for event sampling (in this case the data items ISNC2 and ISCC2 from input options 'SAM-OPT-NC' and 'SAM-OPT-CC' are ignored!).

GSW-PARAM
data: LPARIN (1:11);
monitoring the definition of electroweak parameters and the inclusion of different virtual corrections.
LPARIN(1) = 1: electroweak parameters set with fixed values for the boson masses M_W, M_Z;
= 2: electroweak parameters calculated from fixed M_Z, G_μ.
Default: LPARIN(1) = 2. The definition of boson and fermion masses as far as they are not input from code word "GSW-MASS" and the calculation of coupling constants is done in the subroutine HSSETP.
LPARIN(2) = 0: only Born cross-section without electromagnetic or weak corrections is integrated/sampled;
= 1: Born cross-section including corrections as determined by LPARIN(3) – LPARIN(11). Default: LPARIN(2) = 1.
The following options define the corresponding corrections to be included in the actual calculation (0/1 = no/yes).
LPARIN(3) (0): soft-photon exponentiation *;
LPARIN(4) (1): leptonic QED corrections;
LPARIN(5) (0): quarkonic QED corrections *;
LPARIN(6) (0): lepton–quark interference *;
LPARIN(7) (1): fermionic contributions to the photon self-energy Σ^γ;
LPARIN(8) (0): fermionic contribution to the γ–Z mixing;
LPARIN(9) (0): fermionic contribution to the self-energy of the Z boson;
LPARIN(10) (0): fermionic contribution to the self-energy of the W boson;
LPARIN(11) (0): purely weak contributions to the self-energies, vertex corrections and boxes.

GSW-MASS
data: MW, MZ, MH, MT;
the electroweak mass parameters W and Z boson masses, Higgs mass and the top-quark mass (in GeV). The value given for MW is only used if at the same time LPARIN(1) = 1. Otherwise MW is calculated in the program from the μ decay constant.

PARTON-DIS
data: IPART;
defines the parametrization of parton densities or structure functions applied in the calculation. The available parametrizations (taken from the subroutine PYSTFU of JETSET 6.3 [10]) can be found in the source member HSOURCE3, additional ones can be included easily by the user.
IPART ≤ 100: direct call to parton distributions,
IPART ≤ 200: structure functions are calculated using the parton model relations using the parametrizations defined by IPART-100;
IPART > 200: is foreseen for calls to other parametrizations of structure functions not based on the parton model.
For IPART > 100, only leptonic QED corrections and self-energy contributions can be included and no hadronization is sensible.

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* Not implemented in the present version.

IPART = 0: simple scaling distributions;
= 1: Eichten et al., set 1 of ref. [11];
= 2: Eichten et al., set 2 of ref. [11];
= 3: Duke/Owens, set 1 of ref. [12];
= 4: Duke/Owens, set 2 of ref. [12];
= 5: Glück, Hoffmann, Reya [13];
= 6: Harriman et al., set E of ref. [14];
= 7: Harriman et al., set B of ref. [14].

Default: IPART = 7. The parametrizations of Harriman et al. (IPART = 6 and 7) require information on expansion coefficients contained in external files. This information is read in from unit LUNPD6 (for set E) or LUNPD7 (for set B). It is contained in the members HMRSEDAT and HMRSBDAT of the source file.

NFLAVORS
data: NPYMIN, NPYMAX.
minimal and maximal number of flavors to be included in the cross-section. The flavors are counted from 1 to 6 in the following order: d, u, s, c, b, and t. Defaults are NPYMIN = 1 and NPYMAX = 6.

INT-ONLY
data: INTOPT.
A negative value for INTOPT supresses the call to subroutines needed for the preparation of the sampling steps. Only integration of the differential cross-section is performed in this case. Default: 0.

INT-OPT-NC
data: INC2, INC31, INC32, INC33;
defines the contribution(s) to neutral current interactions for which the integrated cross-section is asked to be calculated in order to prepare the sampling procedure (including estimation of local maxima of the actual distribution function if INTOPT ≥ 0).

INC2: integration for the non-radiative contribution (Born term with virtual and soft corrections); integration by Gaussian quadrature, NAGLIB routine D01FCF;
INC31 < 100: number of iterations for integration of the contribution from initial state leptonic bremsstrahlung by VEGAS;
INC31 > 100: (INC31-100) iterations by VEGAS1;
INC31 > 200: (INC31-200) iterations by VEGAS2;
INC32: monitoring the integration of final-state leptonic bremsstrahlung with the same conventions as for INC31;
INC33: monitoring the integration of the Compton contribution with the same conventions as for INC31.

Defaults are INC2 = INC31 = INC32 = INC33 = 0, no integration. A more detailed explanation of the different VEGAS options is given in appendix B.

INT-OPT-CC
data: ICC2, ICC31, ICC32, ICC33;
same as INT-OPT-NC but for the charged-current interaction.
ICC2: integration for the non-radiative contribution (Born term with virtual and soft corrections);
ICC31: integration of the contribution from initial-state leptonic bremsstrahlung by VEGAS;
ICC32: integration of the contribution from initial-state quarkonic radiation (not yet active);
ICC33: integration of the contribution from final-state quarkonic radiation (not yet active);

INT-POINTS
data: NPOVEG;
upper limit for the number of integration points used by VEGAS. Default is NPOVEG = 1000. Recommendations for the use of this input data are discussed in section 6.

SAM-OPT-NC
data: ISNC2, ISNC31, ISNC32, ISNC33;
monitoring the inclusion of individual contributions to the neutral current cross section for event sampling; default: ISNCx = 0. A contribution is included if the corresponding option is set to 1 or 2, respectively; ISNCx = 2 triggers continued sampling, i.e. information from a previous sampling run with ISNCx ≠ 0 is expected.
ISNC2: non-radiative contribution;
ISNC31: initial-state leptonic bremsstrahlung;
ISNC32: final-state leptonic bremsstrahlung;
ISNC33: Compton contribution.

SAM-OPT-CC
data: ISCC2, ISCC31, ISCC32, ISCC33;
same as SAM-OPT-NC but for the charged current. For the physical content of the charged-current radiative channels, see option "INT-OPT-CC".

RNDM-SEEDS
data: ISDINP, ISDOUT;
monitoring input/output of actual random seeds from/to unit LUNRND.
ISDINP = 0/1: (no) input of seeds;
ISDOUT = 0/1: (no) output of seeds.
Default: ISDINP = ISDOUT = 0.

IOUNITS
data: LUNIN, LUNOUT, LUNRND, LUNDAT, LUNPD6, LUNPD7;
logical unit numbers for in- and output.
LUNIN: for input of parameters as described in this section 4.1 (default: 5);
LUNOUT: for control output and output of results (see section 4.2.1, default: 6);
LUNDAT: for in-/output of results from the integration step from/to an external file (see section 4.4, default: 11);
LUNRND: for in-/output of the random number status from/to an external file (see section 4.4, default: 10);
LUNPD6: for input needed for the parton distributions HMRS(E) (default: 27);
LUNPD7: for input needed for the parton distributions HMRS(B) (default: 28).

START
data: NEVENT
starts the execution of the main program.
NEVENT: number of requested events if any sampling option is activated. Default: NEVENT = 1000.

4.2. Output / scoring of generated events

In this subsection we describe the standard output of the program as well as the way the user may extract the information wanted during event sampling.

4.2.1. Standard output

1. Definition of run parameters.
- All quantities transferred to the program via the input options are echoed immediately after reading the input.
- The final definition of all important parameters is printed before the actual start of the integration/sampling procedure.

2. Integration.

(i) Non-radiative contribution:
The resulting estimate of the integrated non-radiative cross-section and an estimate for its error is printed (presently requested relative accuracy $\Delta I/I = 10^{-3}$).

(ii) Bremsstrahlung contributions:
The program gives the standard output generated by the VEGAS routines, including:
- number of function evaluations per iteration;
- integral and error estimates for the actual iteration;
- accumulated integral and error estimates taking into account results from previous iterations (depending on the entry chosen for the VEGAS routine, compare appendix B and input option "INT-OPT-NC").

3. Sampling.

Actually applied cross-sections and the numbers of generated events are given for each individual contribution. For each run, a header record and a terminating record is written to the common block /HEPEVT/ according to the standards proposed in [15]. The header record contains in addition to the standard quantities parameter definitions and option flags, the final record includes some partial results. Details are given in appendix C.

4.2.2. Scoring of events

The program is designed in such a way that any user action is expected in the user-supplied subroutine HSUSER(ICALL,X,Y,Q2). Here the user may ask for output of the events or the preparation of histograms. This subroutine is called only if event sampling is requested via the input options. The arguments have the following meaning:

ICALL = 1: initial call from the main program to allow the necessary initializations;
= 2: calls for scoring of sampled events (HSUSER is called for each accepted event);
= 3: final call after completion of event sampling.
X,Y,Q2: corresponding kinematical variables of the actual event.

The complete information on each sampled event is transferred to HSUSER via the common block /HEPEVT/ composed according to recent recommendations for event generators [15]. This form was chosen to allow for an easy extension of the program towards the coupling of fragmentation programs. The common block has the structure

```
COMMON /HEPEVT/ NEVHEP, NHEP, ISTHEP (NMXHEP), IDHEP (NMXHEP),
 &                JMOHEP (2, NMXHEP), JDAHEP (2, NMXHEP),
 &                PHEP (5, NMXHEP), VHKK (4, NMXHEP)
```

The important variables are:

NEVHEP:	normally the event number;
NHEP:	the actual number of entries stored in the current event;

IDHEP(IHEP): particle identity, according to the Particle Data Group standard;
PHEP(1:4, IHEP) 4-momentum, in GeV/c.

The conventions for storing the individual particles in this common block are: the scattered lepton has IHEP = 1, IHEP = 2 denotes the scattered quark (or the complete hadronic final state if IPART > 100), and IHEP = 3 the photon. For IPART ≤ 100, i.e. if the parton model is to be used, also the proton remnant is saved on the event record with IHEP = 4 and the convention IDHEP(4) = 90 *, and ISTHEP(4) = 1.

It might also be convenient to use the information of the common block /HSIKP/ which describes the events in terms of Mandelstam invariants of the electron quark subprocess as defined in section 1. The content of this common block is

```
      COMMON /HSIKP/ S,T,U,SS,TS,US,DKP,DKPS,DKQ,DKQS
```

In case of non-radiative events the primed quantitites s', t' and u' (entries SS, TS, and US) are put equal to the unprimed S,T, and U, respectively, and the four dot-products of the photon 4-momentum with the different fermion momenta are set to 0. Note that the real variables of both the common blocks HEPEVT and HSIKP are declared as DOUBLE PRECISION.

4.3. Random number generator

The algorithm for the generator of uniform random numbers used in our program has been taken from ref. [2]. The generated sequence of pseudorandom numbers should be independent of the actual hardware (if a real number has at least 24 significant bits in the internal representation). This generator has a period of about 2^{144}. Optionally, the actual seeds for the generator may be written to an external file (unit number LUNRND) after integration/event sampling is completed in the actual run. Seeds from previous runs may be read from the same unit for continued integration/sampling (compare the input option "RNDM-SEEDS').

4.4. External files to be defined by the user

The program needs two external files to be defined by the user, which are listed in the following:
unit LUNRND: file to store/read random-number seeds (101 double-precision words on the IBM);
unit LUNDAT: information from integration procedures (and potential previous event sampling), needed for (continued) event generation.

Besides quantities necessary for (continued) integration/sampling, also the following parameters characterizing the actual run conditions are written to the corresponding data file: beam properties (code words "EL-BEAM" and "PR-BEAM"), kinematical cuts ("KINEM-CUTS" and "EGAM-MIN"), options for the electroweak effects and parton distributions ("GSW-PARAM" and "PARTON-DIS"). If a data set is used in subsequent runs these parameters are checked for consistency with those defined in the actual job.

4.5. Source files and sample input

The source of the program is divided into several members:

- HSMAIN: Contains the main program, the routines setting the parameters as well as the routines handling input and output of data.

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* There is no standard for the identity of the proton remnant. Whether the proton remnant is treated as a diquark or a system of a baryon and a single quark or something else has to be modeled inside the programs for hadronization.

- HSOURCE1: General sampling routines, applied version of the integration routine VEGAS, routines related to the random-number generator.
- HSOURCE2: Subroutines for the calculation of partial cross sections, kinematical limits, one-loop corrections, etc.
- HSOURCE3: A set of parametrizations of the quark distribution functions. Actually the parton distributions from JETSET 6.3 [10] are supplied, extended by the parametrizations from Harriman, Martin, Stirling and Roberts [14].
- HSSTRFCT: Subroutines for the calculation of structure functions including leptonic QED corrections and boson self-energies.
- HSOURCEC: A set of routines for the calculation of the charged current cross section and corrections.
- HSEXTERN: Substitutes for external routines.

Furthermore, sample jobs for integration and sampling of all contributions are supplied including IBM-JCL and input data:
#NINTNR: integration for the non-radiative NC contribution;
#NINTINI: integration for initial-state bremsstrahlung (NC);
#NINTFIN: integration for final-state bremsstrahlung (NC);
#NINTCMP: integration for the Compton part (NC);
#CINTNR: integration for the non-radiative CC contribution;
#CINTINI: integration for initial-state bremsstrahlung (CC);
#SAMPLE: generation of 1000 events including all contributions (first call);
#SAMPLEC: generation of 1000 events including all contributions (continued sampling).
We also provide an example for the subroutine HSUSER, which may serve as a starting point for the development of user-specific scoring routines: it simply writes some parameters for the actual run and the characteristics of the generated events onto an external file to be assigned to unit LUNEVE.

4.6. External procedures required by the program

Besides those routines supplied by the user for event scoring and output, the program needs an external integration procedure for the calculation of the non-radiative cross-section. Presently, the routine D01FCF from the NAGLIB library is used. But it can be replaced by any other routine for a two-dimensional integration with fixed integration limits for a non-singular integrand. An explicit code as an alternative for D01FCF is provided in the member HSEXTERN. This file contains also some dummy routines which are foreseen to provide the interface to programs which should perform the hadronization of the scattered quark and the proton remnant.

Moreover, a subroutine for the evaluation of the Γ function GAMMA(X) for a real double-precision argument is needed.

5. First experience with the program

The integration of the non-radiative part (job#NINTNR) needed about 12 seconds on an IBM 3090. The integration by VEGAS for the radiative parts (five iterations with maximally 3100 function evaluations each) according to the jobs in the members #NINTINI, #NINTFIN, and #NINTCMP took each about 62 CPU seconds. It is recommended to start with a few iterations using not less than 1000 function evaluations followed by several final iterations with a higher number of integration points (about 10000). A run of # SAMPLE generating 10000 events (both non-radiative and radiative) was finished after about 25 CPU seconds. In the initialization steps for this run we had used 5 iterations with 3100 integration points each, followed further by 3 iterations each with 10000 points.

The time needed for event generation depends on the size of the range of kinematic variables x and y. For small bins the event generation works faster. The time per event increases slightly with the number of generated events. This happens if in the course of event sampling the estimated values of the integrand maxima are corrected and the sampling is re-iterated. It is therefore recommended to check the remaining CPU time (in the subroutine HSUSER) and stop the program in time.

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Appendix A. Definition of kinematical cuts

In the present version of the program the basic constraint on the momentum transfer $Q^2 \geq Q^2_{\text{min}}$ is superimposing all further kinematical constraints. Q^2_{min} may be defined by the user via the option "KINEM-CUTS". In addition, limits on x and y and a minimal hadronic mass W may be given. Additionally, several definitions of the kinematical region may be requested by the user via the input parameters of the option "KINEM-CUTS". In the following we list in detail the kinematical cuts as defined in the program for non-radiative events ($S = 4E_{\text{e}}E_{\text{p}}$).

ICUT = 1: x-limits and Q^2_{min} from input accepted, y-limits and W_{min} ignored:

$$Q^2_{\text{min}} \leq Q^2 \leq Q^2_{\text{max}} = x^{\text{input}}_{\text{max}} S, \quad x_{\text{min}} = \text{Max}\left\{x^{\text{input}}_{\text{min}},\, Q^2_{\text{min}}/S\right\} \leq x \leq x^{\text{input}}_{\text{max}}.$$

ICUT = 2: As ICUT = 1 with an additional lower cut on the mass of the final-state hadrons,

$$W^2_{\text{min}} \leq W^2 = (1-x)yS + M^2_{\text{P}}.$$

W_{min} will be set automatically to M_{P} if the input is smaller. The additional restriction of W^2 translates into a modification of the lowest allowed Q^2 value in the actual calculation:

$$Q^2_{\text{min}} = \text{Max}\left\{\left(Q^2_{\text{min}}\right)^{\text{input}}, \frac{x}{1-x}\left(W^2_{\text{min}} - M^2_{\text{P}}\right)\right\},$$

and

$$x_{\text{max}} = \text{Min}\left\{x^{\text{input}}_{\text{max}},\, 1 - \left(W^2_{\text{min}} - M^2_{\text{P}}\right)/S\right\}.$$

ICUT = 3: All given limits ($x_{\text{min,max}}$, $y_{\text{min,max}}$, Q^2_{min}, and W_{min}) are accepted. The actually applied limits are calculated from the most-restrictive input conditions resulting in:

$$Q^2_{\text{min}} = \text{Max}\left\{x_{\text{min}}y_{\text{min}}S, \left(Q^2_{\text{min}}\right)^{\text{input}}, \frac{x_{\text{min}}}{1-x_{\text{min}}}\left(W^2_{\text{min}} - M^2_{\text{P}}\right)\right\} \leq Q^2,$$

$$x_{\text{min}} = \text{Max}\left\{x^{\text{input}}_{\text{min}},\, Q^2_{\text{min}}/y_{\text{max}}S\right\},$$

$$x_{\text{max}} = \text{Min}\left\{x^{\text{input}}_{\text{max}},\, 1 - \left(W^2_{\text{min}} - M^2_{\text{P}}\right)/y_{\text{max}}S\right\},$$

$$y_{\text{min}} = \text{Max}\left\{y^{\text{input}}_{\text{min}},\, Q^2_{\text{min}}/x_{\text{max}}S, \frac{W^2_{\text{min}} - M^2_{\text{P}}}{(1-x_{\text{min}})S}\right\}.$$

For radiative events, analogous constraints are respected depending on the value of ICUT. In this case the limits on the hadronic final-state mass does not change the input values for the cuts on x and y or Q^2, but restricts the phase space of the bremsstrahlung photon.

Appendix B. Remarks on the integration routine VEGAS

One of the most important features of the integration algorithm realized in VEGAS is the subdivision of the integration volume in order to concentrate evaluations of the integrand in regions where it takes large values. This subdivision into hypercubes is modified after each iteration according to the results of this last integral estimation. If a calculation with a given number of iterations is finished, the information on the actual grid structure together with results for the integral and error estimates are stored on an external file. This information may be used as input for further iterations to calculate the integral. Finally it is used to construct an optimized density for sampling in the event-generation procedure. A detailed description of the method is given in ref. [1]. The VEGAS code offers several entries referred to in the description of the input options "INT-OPT-NC" and "INT-OPT-CC":

- VEGAS: Cold start of the integration procedure with uniform grid; no information is required from external files.
- VEGAS1: Restart of the iteration procedure to estimate the integral; the grid structure is used from the previous run, but estimates of the integral and its error accumulated in the previous run(s) are discarded. (The information necessary is read from the corresponding external file.)
- VEGAS2: Restart of the iteration procedure using both the grid information and the accumulated estimates of the integral and its error from the previous run(s).

Appendix C. Conventions for header and final record

Before event generation, a header record is written to the common block /HEPEVT/ with NEVHEP $= -1$. The content of its first entry (IHEP = 1) is according to the standard [15]. The other entries have the following meaning:

NHEP = 73, number of entries in the header record;
PHEP(1,2) = EELE, energy of the initial electron in GeV;
PHEP(1,3) = POLARI, polarization of the initial electron;
PHEP(1,4) = EPRO, energy of the initial proton in GeV;
PHEP(1,5) = XMIN, minimum of the leptonic x;
PHEP(1,6) = XMAX, maximum of the leptonic x;
PHEP(1,7) = YMIN, minimum of the leptonic y;
PHEP(1,8) = YMAX, maximum of the leptonic y;
PHEP(1,9) = Q2MIN, minimum of the leptonic momentum transfer Q^2 in GeV^2;
PHEP(1,10) = WMIN, minimum of the invariant mass of the hadronic final state in GeV;
PHEP(1,11) = EGMIN, minimum of the photon energy in GeV;
PHEP(1,12) = MW, W-boson mass in GeV;
PHEP(1,13) = MZ, Z-boson mass in GeV;
PHEP(1,14) = MH, Higgs-boson mass in GeV;
PHEP(1,15) = MT, top-quark mass in GeV;
ISTHEP(2) = LLEPT, charge of the initial lepton;
ISTHEP(3) = ICUT, flag for kinematical cuts;

ISTHEP(4:15) = LPARIN(1:12), flags for the definition of electroweak parameters and partial electroweak corrections;
ISTHEP(16) = IPART, flag for the parametrization of quark distribution functions or structure functions;
ISTHEP(17) = NPYMIN, minimal number of flavors;
ISTHEP(18) = NPYMAX, maximal number of flavors;
ISTHEP(19) = LUNIN, logical unit number for parameter input;
ISTHEP(20) = LUNOUT, logical unit number for standard output;
ISTHEP(21) = LUNTES, logical unit number for test output;
ISTHEP(22) = LUNRND, logical unit number for in- and output of the random number generator;
ISTHEP(23) = LUNDAT, logical unit number for in- and output of results of the integration step;
ISTHEP(24) = NINP, logical unit number for VEGAS input;
ISTHEP(25) = NOUTP, logical unit number for VEGAS output;
ISTHEP(26:30) = flags for integration of non-radiative partial cross-sections (internally denoted by INT2(1:5);
ISTHEP(26) = INC2 from input code word "INT-OPT-NC";
ISTHEP(27) = ICC2 from input code word "INT-OPT-CC";
ISTHEP(28:30) = not used;
ISTHEP(31:45) = flags for integration of radiative partial cross-sections (internally denoted by INT3(1:15));
ISTHEP(31) = INC31 from input code word "INT-OPT-NC";
ISTHEP(32) = INC32 from input code word "INT-OPT-NC";
ISTHEP(33) = INC33 from input code word "INT-OPT-NC";
ISTHEP(34:36) = not used;
ISTHEP(37) = ICC31 from input code word "INT-OPT-CC";
ISTHEP(38) = ICC32 from input code word "INT-OPT-CC";
ISTHEP(39) = ICC33 from input code word "INT-OPT-CC";
ISTHEP(40:45) = not used;
ISTHEP(46) = NPOVEG, maximal number of points used in the VEGAS integration;
ISTHEP(47) = NUMINT, not active in version 4.0;
ISTHEP(48) = NPHYP, not active in version 4.0;
ISTHEP(49:53) = flags for the inclusion of non-radiative partial cross-sections in event generation (internally denoted by ISAM2(1:5));
ISTHEP(49) = ISNC2 from input code word "SAM-OPT-NC";
ISTHEP(50) = ISCC2 from input code word "SAM-OPT-CC";
ISTHEP(51:53) = not used;
ISTHEP(54:68) = flags for the inclusion of radiative partial cross sections in event generation (internally denoted by ISAM3(1:15));
ISTHEP(54) = ISNC31 from input code word "SAM-OPT-NC";
ISTHEP(55) = ISNC32 from input code word "SAM-OPT-NC";
ISTHEP(56) = ISNC33 from input code word "SAM-OPT-NC";
ISTHEP(57:59) = not used;
ISTHEP(60) = ISCC31 from input code word "SAM-OPT-CC";
ISTHEP(61) = ISCC32 from input code word "SAM-OPT-CC";
ISTHEP(62) = ISCC33 from input code word "SAM-OPT-CC";
ISTHEP(63:68) = not used;
ISTHEP(69) = INTOPT, flag for integration in- or excluding preparation of the sampling step;
ISTHEP(70) = IPRINT, flag for test output;

ISTHEP(71) = ISDINP, flag for input of random-number seeds;
ISTHEP(72) = ISDOUT, flag for output of random-number seeds;
ISTHEP(73) = NEVENT, requested number of events.

The following list shows the content of the final record with NEVHEP = -2. This record contains output of the program.

NHEP = 44, number of entries in the final record;
PHEP(1,1) = SIGTOT, total cross-section;
PHEP(1,2) = SIGTRR, estimated error of the total cross-section;
PHEP(1,3 : 22) = SIGG(1 : 20), partial cross-sections;
PHEP(1,23 : 42) = SIGGRR(1 : 20), estimated errors of partial cross-sections;
PHEP(1,43) = SW2, weak mixing angle s_W^2;
PHEP(1,44) = MW, W-boson mass; may be changed from its input value;
ISTHEP(1) = NEVENT, total number of generated events;
ISTHEP(2 : 22) = NEVE(1 : 21), partial event numbers for each channel.

References

[1] G.P. Lepage, J. Comput. Phys. 27 (1978) 192.
[2] G. Marsaglia and A. Zaman, Towards a universal random number generator, Florida State Univ. Preprint FSU-SCRI (1987). See also F. James, Comput. Phys. Commun., 60 (1990) 329.
[3] M. Böhm and H. Spiesberger, Nucl. Phys. B 294 (1987) 1081.
[4] D.Yu. Bardin, C. Burdik, P.Ch. Christova and T. Riemann, Z. Phys. C 42 (1989) 679.
[5] G. Schuler and H. Spiesberger, in preparation.
[6] J. Feltesse, Proc. HERA Workshop, Hamburg, 1987, Vol. 1, ed. R.D. Peccei, p. 33.
[7] A. Kwiatkowski, H.-J. Möhring and H. Spiesberger, Z. Phys. C 50 (1991) 165.
[8] A. Kwiatkowski, PhD thesis.
[9] S. de Jong and J. Vermaseren, AXO User Manual, NIKHEF-H Report 1987.
[10] T Sjoestrand and M. Bengtsson, Comput. Phys. Comm. 43 (1987) 367.
[11] E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Rev. Mod. Phys. 56 (1984) 579.
[12] D.W. Duke and J.F. Owens, Phys. Rev. D 30 (1984) 49.
[13] M. Glück, E. Hoffmann and E. Reya, Z. Phys. C 13 (1982) 119.
[14] P.N. Harriman, A.D. Martin, W.J. Stirling and R.G. Roberts, preprint RAL-90-007 (1990).
[15] G. Altarelli, R. Kleiss and C. Verzegnassi (eds.), Z Physics at LEP 1, Vol. 3: Event generators and software, CERN 89-08 (21 September 1989).
B. Bambah et al., QCD generators for LEP, CERN-TH. 5466/89 (July 1989).

TEST RUN OUTPUT

Here we reproduce the sample jobs #NINTNR (integration of the neutral current non-radiative cross-section) and #NCSAMP (first call for the generation of 1000 events including the contributions of all channels for neutral and charged current scattering). These jobs run on the IBM-3090 at DESY.

```
// JOB CLASS=K,MSGLEVEL=(2,0),TIME=(00,30),NOTIFY=F01MOE
//* ******************************************************************
//*
//*    HERACLES V 4.0  / INTEGRATION FOR NON-RADIATIVE CONTRIBUTION
//*
//* ******************************************************************
// EXEC VFORTCLG,
//             CPRT=DUMMY,
//             LLB1='F01MOE.HERACLES.V40.L',
//             LLB2='SYSW1.DNAGLIB'
//C.SYSIN DD *
 MACRO HSUSER
//L.SYSIN  DD *
      INCLUDE SYSLIB(HSMAIN)
      INCLUDE SYSLIB(HSOURCE1,HSOURCE2,HSOURCE3)
      INCLUDE SYSLIB(HSOURCEC,HSSTRFCT)
      ENTRY EPGEN
//G.FT10F001  DD  DSN=F01MOE.HER.V40.RNDNRS,UNIT=FAST,
//       DCB=(RECFM=VBS,BLKSIZE=6233,LRECL=32760),
//       DISP=OLD
//G.FT11F001  DD  DSN=F01MOE.HER.V40.DATA,UNIT=FAST,
//       DCB=(RECFM=VBS,BLKSIZE=6233,LRECL=32760),
//       DISP=OLD
//G.FT27F001 DD DSN=I02SPI.HMRSE.DAT,UNIT=FAST,DISP=SHR
//G.FT28F001 DD DSN=I02SPI.HMRSB.DAT,UNIT=FAST,DISP=SHR
//G.SYSIN DD *
TITLE
TEST RUN //  INTEGRATION FOR NON-RADIATIVE CONTRIBUTION
IOUNITS
            5  6  11  10  27  28
GSW-PARAM
            2 1 0 1 0 0 1 0 0 0 0
EL-BEAM
            30D0  0D0   -1
PR-BEAM
            820D0
KINEM-CUTS
            3   1D-04  5D-01  1D-02  0.99D0    4D0   2D0
EGAM-MIN
            0D0
INT-OPT-NC
            1     0      0      0
INT-POINTS
            1000
SAM-OPT-NC
            0 0 0 0
PARTON-DIS
            7
NFLAVORS
            0   5
RNDM-SEEDS
            0   1
START
            1000
```

The following JCL calls HERACLES to produce 1000 events. The information of the preceeding initialization steps is supplied from the dataset HER.V40.DATA. The generated events are written to the file HER.V40.EVENTS. Of course, the names and specifications of these files have to be adjusted to the specific environment. In this second example only non-default input options are explicitly given.

```
// JOB CLASS=A,MSGLEVEL=(2,0),TIME=(00,10),NOTIFY=F01MOE
//* *****************************************************************
//*
//*    HERACLES V 4.0 / SAMPLING OF 1000 EVENTS
//*                     FOR NEUTRAL AND CHARGED CURRENT INTERACTIONS
//*                     WITHOUT CUT ON PHOTON ENERGY
//*
//*                     EVENTS ARE WRITTEN TO UNIT LUNEVE=31
//*
//* *****************************************************************
// EXEC VFORTCLG,
//             LLB1='F01MOE.HERACLES.V40.L',
//             LLB2='SYSW1.DNAGLIB',
//             LLB3='R01UTL.CERN.PACKLIB',
//             LLB4='R01UTL.CERN.GENLIB',
//             LLB5='R01UTL.CERN.KERNLIB'
//C.SYSIN DD *
 MACRO HSUSER
//L.SYSIN  DD *
      INCLUDE SYSLIB(HSMAIN)
      INCLUDE SYSLIB(HSOURCE1,HSOURCE2,HSOURCE3)
      INCLUDE SYSLIB(HSOURCEC,HSSTRFCT)
      ENTRY EPGEN
//G.FT10F001  DD  DSN=F01MOE.HER.V40.RNDNRS,UNIT=FAST,
//       DCB=(RECFM=VBS,BLKSIZE=6233,LRECL=32760),
//       DISP=OLD
//G.FT11F001  DD  DSN=F01MOE.HER.V40.DATA,UNIT=FAST,
//       DCB=(RECFM=VBS,BLKSIZE=6233,LRECL=32760),
//       DISP=OLD
//G.FT31F001  DD  DSN=F01MOE.HER.V40.EVENTS,UNIT=FAST,
//       DISP=OLD
//G.FT27F001 DD DSN=I02SPI.HMRSE.DAT,UNIT=FAST,DISP=SHR
//G.FT28F001 DD DSN=I02SPI.HMRSB.DAT,UNIT=FAST,DISP=SHR
//G.SYSIN DD *
TITLE
TEST RUN //  GENERATION OF 1000 NC/CC-EVENTS / WRITTEN TO UNIT 31
IOUNITS
            5  6  11  10  27  28
KINEM-CUTS
            3   1D-04  5D-01  1D-02  0.99D0    4D0   2D0
SAM-OPT-NC
            1 1 1 1
SAM-OPT-CC
            1 1 0 0
RNDM-SEEDS
            0   1
START
            1000
```