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HERACLES.
An Event Generator for ep Interactions at HERA Including Radiative Processes
VERSION 4.6

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Abstract: A Monte Carlo event generator simulating neutral and charged current *ep* interactions at HERA energies and beyond is described. The actual version 4.6 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 or the quark line as well as self energy corrections and the complete set of one-loop weak corrections can be included. The new version includes the background from radiative elastic scattering $ep \to ep\gamma$.

1 Program Summary

Title of the program:	HERACLES
Version number:	4.6 (Jan. 1996)
Computer:	VAX, IP19(mips)
Program language:	FORTRAN-77
Number of program lines:	about 16,500
Other programs used:	VEGAS [1], multidimensional Monte Carlo integration.
	RNDM(), random number generator. The method is taken from ref. [2].

	D01AJF and D01FCF, one- and two-dimensional integration routines of a non-singular integrand with constant integration limits.
	GAMMA, the Γ function.
	DIVDIF, an interpolation routine.
	The code of all these programs is contained in the source code of HERACLES. Alternatively, routines from the DESY or CERN libraries, and in the case of D01AJF amd D01FCF the NAGLIB, can be used.
External files needed:	Files for random number seeds and for information of the integration step are needed, see section 4.4 for details.
Method of solution:	Monte Carlo event generator.
Typical running time:	Depending on the actual requirements (parameters, requested contributions, kinematical limits, initialization); a typical example is: 1000 radiative events need 0.4 *sec* CPU on an IP19. For a more detailed discussion see sect. 6.

2 Introduction

In this note we present a technical description of the event generator HERACLES, version 4.6, for the simulation of deep inelastic $e^{\pm}p$ collisions via the neutral current as well as charged current interactions at HERA energies. The event generator HERACLES includes the leptonic corrections as well as radiation from the quark line and interference of leptonic and quarkonic radiation and the complete one–loop virtual corrections using the results of Refs. [3, 4, 5].

The most important capabilities of the generator are:

- It allows integration of the differential cross sections for $\ell p \rightarrow \ell' X$ and $\ell p \rightarrow \ell' \gamma X$ over kinematical regions which can be defined in terms of the variables x, y, Q^2 and W, the mass of the hadronic final state. x, y, and Q^2 are determined from the outgoing lepton's energy and scattering angle. As well, in the calculation of the cross section for $\ell p \rightarrow \ell' \gamma X$ 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 mode. 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 QED corrections (comprising soft and hard bremsstrahlung and the corresponding virtual corrections). For the neutral current reaction, these parts describe leptonic initial state radiation, leptonic final state radiation, a contribution called Compton part, and quarkonic radiation. The separation of the total cross section into these channels is obtained with the help of a partial fractioning which is *not unique*. Note in particular that this separation is not a separation of the phase space for photon emission and each channel is defined on the whole phase space. In the case of the charged current reaction, there is one radiative channel comprising emission of photons from the initial lepton and the final quark. For the charged current process radiative corrections are taken into account approximately only, the precision being of the order of 2 %.

- 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 or structure functions. In particular, a non-zero longitudinal structure function F_L can be included. Note that in this case it is not possible to include quarkonic radiation and its interference with leptonic radiation.
- The program gives reliable results in the whole phase space also in the photoproduction limit, $Q^2 \to 0$, and for large $y \to 1$.
- The new version 4.6 includes elastic $ep \to ep$ scattering and the radiative tail $ep \to ep\gamma$.

HERACLES itself generates events at the parton level. The interface DJANGO6 which calls routines from LEPTO and JETSET has to be used for a complete event simulation including fragmentation and hadronization of the scattered quark and the proton remnant [6].

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 should lie in the region

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

The limitation to $Q^2 \geq 4\ GeV^2$ of former versions has been removed. The user has to make sure by himself that parametrizations for structure functions are used which are valid everywhere in the considered kinematic region. A number of options for a sensible low Q^2 behaviour of structure functions have been made available.

Already former versions of HERACLES were able to describe the differential cross section for scattering of polarized electrons and positrons with an accuracy of better than 5% for not too small or too 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. Since version 4.1 also the interference of radiation from the lepton and the quark line together with two-photon box diagrams is included, and the accuracy of versions 4.1 and higher is only restricted by higher order corrections beyond $\mathcal{O}(\alpha)$. Also the measurement of charge and polarization asymmetries is described correctly since version 4.1.

A description of the physics that is simulated by HERACLES can be found in [7]. Section 3 contains 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. Further details are given in two appendices. First results from HERACLES have been published in [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 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, needed 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.

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 output 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; for details see 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 (see code-word 'SAM-OPT-NC' below).

  EGMIN > 0.0: Only hard-photon bremsstrahlung with E_γ above EGMIN is 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!)

- 'THMIN-QRAD'
  data: TCUTQ, TCUTQS
  definition of angular cuts for the separation of photons from the incoming and outgoing quarks (in *rad*, defaults: TCUTQ=TCUTQS=0.25).

- '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 the values of 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) (3) :	flag for inclusion of higher order contributions:
= 0 :	no higher order corrections;
≥ 1 :	terms of $\mathcal{O}(\alpha^2 m_t^4)$ included;
≥ 2 :	terms of $\mathcal{O}(\alpha\alpha_S m_t^2)$ included;
≥ 3 :	running $\alpha(Q^2)$ is used for leptonic QED corrections;
LPARIN(4) (1) :	leptonic QED corrections;
LPARIN(5) (0) :	quarkonic QED corrections;
LPARIN(6) (0) :	lepton-quark interference[2];
LPARIN(7) (2) :	fermionic contributions to the photon self energy Σ^γ;
= 0 :	not included;
= 1 :	parametrization with the help of quark masses [10];
= 2 :	parametrization from [11];
LPARIN(8) (0) :	fermionic contribution to the $\gamma - Z$ 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.

[2]The contribution from lepton-quark interference can be requested only if both the leptonic and the quarkonic corrections are activated at the same time.

- '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'
  has been removed and replaced by the following:

- 'STRUCTFUNC'
  data: ISTRFC
  defines the parametrization of parton densities or structure functions applied in the calculation. The input is defined by

  ISTRFC = ILQMOD*100000 + ILIB*10000 + ICODE

  where

ILIB = 1 :	to choose parton distribution functions from PYSTFU. The subroutine PYSTFU has been taken from LEPTO 6.3 [12] and modified for the use in HERACLES.
ILIB = 2 :	to use PDFLIB [13]. Calls are performed via PYSTFU, but the corresponding line in the source code has to be enabled and the library to be provided by the user.
ILIB = 3 :	to use PAKPDF [14]. Again, calls are performed via PYSTFU.

  and

ICODE =	VALUE(1), the identification code for the parametrization of parton distribution functions for PDFLIB ('MODE').
ICODE =	IPAR*100 + ISET, the identification code for use of the library PAKPDF.

  ILQMOD specifies the treatment of the low Q^2 behaviour of the structure functions.

ILQMOD = 0:	use unmodified parton distribution functions for all Q^2.
ILQMOD = 1:	apply exponential low Q^2 suppression factor to parton distribution functions [15].
ILQMOD = 2:	for low Q^2 (for $Q^2 < 6$ GeV^2) use F_1 and F_2 parametrizations from Brasse [16] (for $W < 2$ GeV) and Stein [17] (for $W > 2$ GeV). For large Q^2, parton distribution functions as determined by ICODE are used.
ILQMOD = 3:	for $Q^2 < 6$ GeV^2 use parametrizations from Abramowicz, Levy, Levin, and Maor [18] (for $W > 2$ GeV) together with Brasse (for $W < 2$ GeV). If ICODE = 0, the ALLM parametrization is used for high Q^2 as well; if ICODE $\neq 0$, for large Q^2 the parton distributions as requested by ICODE are combined with the ALLM parametrization.

ILQMOD = 4:	For $x < 0.1$ and $\nu > 10$ GeV, the parametrization by Badełek and Kwieciński [19] is used. For $\nu < 10$ GeV, $x < 0.1$, the Brasse and Stein parametrization is used. At larger x, the parton distribution functions from MRS, set D'_- [20] have to be used. NOTE: other combinations of BK with PDF's are inconsistent! It is recommended to use ILQMOD = 4 together with ICODE = 0, in which case the MRS D'_- set is automatically chosen.
ILQMOD = 5:	The Donnachie–Landshoff parametrization [21] for $Q^2 < 10$ GeV^2 together with parton distribution functions are used. If ICODE = 0, the set MRS $B235$ [22] is chosen, since this gives the smallest discontinuities of the cross section.

The default values are ILQMOD = 1 (exponential low Q^2 suppression), ILIB = 1 (PDF's from PYSTFU) and ICODE = 7 (Morfin Tung, set 3)

For ILQMOD $\geq$ 2, only leptonic QED corrections and self energy contributions can be included and no hadronization is sensible. The set of parton distribution functions provided with the present version and accessible by choosing ILIB = 1 is as follows:

ICODE = 0 : Simple scaling distributions;
= 1 : Eichten et al., set 1 of Ref. [24];
= 2 : Eichten et al., set 2 of Ref. [24];
= 3 : Duke/Owens, set 1 of Ref. [25];
= 4 : Duke/Owens, set 2 of Ref. [25];
= 5 : Morfin/Tung, set 1 of Ref. [26];
= 6 : Morfin/Tung, set 2 of Ref. [26];
= 7 : Morfin/Tung, set 3 of Ref. [26];
= 8 : Morfin/Tung, set 4 of Ref. [26];
= 9 : Glück, Reya, Vogt, LO [27];
= 10 : Glück, Reya, Vogt, HO [27];

Default: ISTRFC = 110007.
NOTE that not all combinations of ILQMOD and ICODE result in cross sections which are continuous functions of x and Q^2. In some cases, discontinuities are considerable and result in a bad convergence of the integration routines.

- 'EP-DIPOLE'
  data: IDIPOL
  to include (if non-zero) the parametrization of [17] for the deviation of the elastic ep form factors from the simple dipole form.
  Default: IDIPOL = 0.

- 'FLONG'
  data: IFLOPT
  for the inclusion of the longitudinal structure function F_L. The definition of IFLOPT coincides with the definition of LST(11) of LEPTO 6.3 [12]:

IFLOPT = LQCD + LTM*10 + LHT*100

and LQCD, LTM and LHT specifies whether QCD contributions, target mass effects and higher twist should be included. See the manual of LEPTO 6.1 [12] for details. HERACLES calls modified routines from LEPTO 6.3 to calculate F_L either event–by–event when LQCD = 2 or LTM = 2 (time–consuming) or by using a grid and linear interpolation for LQCD = 1 or LTM = 1.
For the calculation of radiative corrections, F_L is needed for small Q^2, also in the limit $Q^2 \to 0$. The prescription for $F_L(Q^2 \to 0)$ is determined by ILQMOD:

ILQMOD = 2:	The Brasse and Stein parametrizations with $R = 0.18$ is used to calculate F_L.
ILQMOD = 3:	F_L is calculated by the ALLM parametrization.
otherwise:	F_L is calculated from perturbative QCD. For Q^2 values smaller than $Q_0^2 = 6$ GeV^2, F_L is assumed to be independent of Q^2 and its value is given by $F_L(Q^2 = Q_0^2)$.

The default value is IFLOPT = 0

- 'ALFAS'
  data: MST111, MST115, PAR111, PAR112
  information defining the value of α_s needed for the inclusion of F_L. α_s enters the calculation of F_L and is evaluated in the function routine ULALPS. The routine ULALPS has been taken from JETSET 7.3 and modified for the use in HERACLES. The meaning of the input data corresponds to the parameters MSTU(111), MSTU(115), PARU(111), PARU(112) of JETSET 7.3 and is as follows:

MST111 :	Order of α_s evaluation in ULALPS: = 0: fixed α_s at the value of PAR111. = 1: first–order running α_s. = 2: second–order running α_s. (Default = 1).
MST115 :	Treatment of the α_s singularity at $Q^2 \to 0$: = 0: allow it to diverge like $1/\ln(Q^2/\Lambda^2)$. = 1: soften the divergence to $1/\ln(1+Q^2/\Lambda^2)$. = 2: freeze Q^2 evolution below $Q_0^2 = 4\,GeV^2$. (Default = 0).
PAR111 :	The fixed value of α_s assumed in ULALPS when MST111 = 0. (Default = 0.20).
PAR112 :	Λ used in running α_s in ULALPS. (Default = 0.25).

- '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, INC34, IEL2, IEL31, IEL32, IEL33
  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 :	If INC2=1, 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; here the iteration procedure is restarted 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).
INC31 $>$ 200:	(INC31-200) iterations by VEGAS2: the iteration procedure is restarted using both the grid information and the accumulated estimates of the integral and its error from the previous run(s).
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;
INC34 :	monitoring the integration of the contribution from radiation from the quark line with conventions as for INC31;
IEL2 :	if IEL2=1, integration for the non-radiative elastic ep scattering (including virtual and soft corrections); integration by Gaussian quadrature, NAGLIB routine D01FCF;
IEL31 :	monitoring the integration of the quasi-elastic radiative tail from initial-state leptonic bremsstrahlung (same conventions as above for INC31);
IEL32 :	monitoring the integration of the quasi-elastic radiative tail from final-state leptonic bremsstrahlung (conventions as for INC31);
IEL33 :	monitoring the integration of the quasi-elastic radiative tail due to the Compton contribution (same conventions as for INC31);

  Defaults are 0 for all data items, no integration.

- '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. The default value is NPOVEG = 1000. Recommendations for the use of this input data are discussed in section 6.

- 'SAM-OPT-NC'
  data: ISNC2, ISNC31, ISNC32, ISNC33, INC34
  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, resp.; ISNCx=2 triggers continued sampling, i.e. information from a previous sampling run with ISNCx$\neq$ 0 is expected.

ISNC2 :	non-radiative contribution;
ISNC31 :	initial-state leptonic bremsstrahlung;
ISNC32 :	final-state leptonic bremsstrahlung;
ISNC33 :	Compton contribution;
ISNC34 :	quarkonic radiation;
ISEL2 :	non-radiative elastic scattering $ep \to ep$;
ISEL31 :	quasi-elastic radiative tail: initial-state leptonic bremsstrahlung;
ISEL32 :	quasi-elastic radiative tail: final-state leptonic bremsstrahlung;
ISEL33 :	quasi-elastic radiative tail: 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: LUNOUT, LUNRND, LUNDAT, LUNPD6, LUNPD7
  logical unit numbers for in- and output.

LUNOUT: for standard output (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: obsolete, not used.

LUNPD7: obsolete, not used

- '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

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. The results of the integration step are:

(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 input option 'INT-OPT-NC').

After event sampling, the 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 [29]. 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 B.

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 [29]. 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 ILQMOD ≥ 2), and IHEP = 3 the photon. For ILQMOD ≤ 1, *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[1], 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.

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.

[1] 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.

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 and/or 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 provided in one file `heracles_v46.f`. In addition, an example of a user routine `hsuser.f` and a Makefile (that worked on the Desy x4u2-cluster) can be obtained.

The whole package, including sample output and manual can be copied from `http://www.desy.de/~hspiesb/heracles.html`.

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. In former versions, the routine D01FCF from the NAGLIB library is used, but in the present version it was replaced by a Gauss-integration routine. The source code 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. The CERN library routine DIVDIF is needed for the calculation of structure functions from Refs. [16, 17].

4.7 CPU Time

It is recommended to start the integration step with few iterations using not less than 1,000 function evaluations followed by several final iterations with a higher number of integration points (about 10,000).

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 is corrected and the sampling re-iterated. It is therefore recommended to check the remaining CPU time (in the subroutine HSUSER) and stop the program in time.

On the Desy x4u2-workstation (IP19-mips), the generation of 500,000 events took 35 *min* CPU-time, including integration.

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Appendix A: Definition of kinematical cuts

In the present version of the program the basic constraint on the momentum transfer $Q^2 \geq Q^2_{min}$ 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 ($S = 4E_eE_p$).

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

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

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

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

  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:

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

  and

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

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

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

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

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

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

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: 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 [29]. 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):	= ISTRFC, 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 4.6;
ISTHEP(48): = NPHYP, not active in version 4.6;
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 ouput;
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.