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The Monte Carlo program LESKO-F for deep inelastic $e^{\pm}p \rightarrow e^{\pm}$ X scattering at HERA including QED bremsstrahlung from the lepton line

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A Monte Carlo event generator for deep inelastic electron (positron) proton neutral current scattering at HERA energies is described. It includes $\mathcal{O}(\alpha)$ QED bremsstrahlung from the lepton line and allows for longitudinal polarization of the lepton beam. Final particles are produced on the parton level, i.e. the final state is described by the four-momenta of lepton, quark, photon and proton remnant. Information on each generated event is stored in the standardized HEPEVT event record. The program is constructed in such a way that it may be easily connected with other event generators and/or detector simulation programs. Some examples of numerical results of this program are presented.

PROGRAM SUMMARY

Title of the program: LESKO-F version 2.2

Catalogue number: ACJZ

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

Licensing provisions: none

Computer: IBM 3090 300S VF; *Installation*: DESY, Hamburg

Operating system: MVS/XA and JES3 with TSO

Programming language used: FORTRAN 77

Memory required to run with typical data: 45000 words

No. of bits in a word: 32

Peripherals used: terminal or line (laser) printer

No. of lines in distributed program, including test data etc.: 3933

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Keywords: radiative corrections, deep inelastic, Monte Carlo simulation, bremsstrahlung, quantum electrodynamics (QED), spin polarization, electroweak theory, structure functions

Nature of physical problem
In deep inelastic electron–proton scattering the QED radiative corrections, in particular the effects due to bremsstrahlung from the lepton line, are well known, in some regions of the phase space, to be rather big, even of the order of 100%. These effects have to be calculated if we want to extract *physically significant* information from the experimental data, e.g. for the measurement of the proton structure functions. The QED radiative effects, as it is generally known, depend substantially on the properties of the experimental set-up (resolutions, acceptance) and on the event selection criteria in the data analysis (triggers, cut-off's). A Monte Carlo event generator is a very helpful tool and the only one which is able to bring these important relations under control.

Method of solution
The Monte Carlo simulation of the process $e^{\pm}p \to e^{\pm}X$ is applied to analyse the effects of bremsstrahlung from the lepton beam. The electron (positron)–proton scattering process is described according to the parton model assumptions by hard lepton–quark subscattering which is mediated by the standard electroweak interaction i.e. photon and Z^0 boson exchange. The photon emission from leptons is described in the framework of QED. Some realistic cuts are included at the level of the event generation and other ones may be imitated by rejecting some of the generated events.

Restrictions on the complexity of the problem
The incoming $e^{\pm}$ may have nonzero spin polarization. Single bremsstrahlung photon is emitted only from the lepton (initial and final states), not from the quark. QCD radiative effects are not included in the simulation, although the proton structure functions have a QCD-style scaling violation property. The structure of the MC algorithm allows to include QCD effects in the future.

Typical running time
Efficiency is about 1200 events per IBM 3090 300S CPU second for parton distribution functions in Duke and Owens parametrization.

LONG WRITE-UP

1. Introduction

QED radiative corrections will significantly distort distributions of observed quantities in the deep inelastic scattering at the HERA experiments. This phenomenon was seen in older deep inelastic experiments [1] and the corresponding QED correction for HERA was estimated first in ref. [2] using the calculation of ref. [3]. The complete $\mathcal{O}(\alpha)$ electromagnetic and weak corrections have been calculated by Bardin et al. [4] and Böhm and Spiesberger [5], see also ref. [6]. The most pronounced distortions are due to an emission of a bremsstrahlung photon from the electron beam. Such an emission causes the momentum transfer squared Q_e^2 and the Bjorken variable x_e obtained from the momentum of the scattered electron to be different from the actual momentum transfer Q^2 exchanged in the elementary hard electron–quark scattering process and the real x being the fraction of the proton momentum carried by the quark before the scattering [7,8]. This kinematical effect is the reason of large changes in the distributions of some physically interesting quantities, as for example the proton structure functions. Actual calculations show that a differential cross section $d^2\sigma/dx_e\, dy_e$, where $y_e = Q_e^2/s_0 x_e$ and s_0 is the total center of mass energy squared, may considerably exceed an original cross section $d^2\sigma/dx\, dy$ in the region of the high y_e and low x_e. In principle it is possible to estimate an influence of this bremsstrahlung effect on the obtained distributions by a simultaneous measurement of the momenta of the scattered electron and quark (jet). Unfortunately, such a measurement is not possible in the whole region of (x, Q^2) due to detector resolution limitations [7,9]. In the very interesting region for $x < 0.01$ it is only possible to measure the electron momenta, but not the quark ones. The most flexible tool to study these effects and to study methods of eliminating them from the experimental data with regard to a realistic detector acceptance, selection criteria etc. is a Monte Carlo event generator of the type presented in this article. One of such methods, for the measurement of the proton structure functions at HERA, was recently proposed in ref. [10]. Let us not that another Monte Carlo program for deep inelastic ep scattering, named HERACLES, is available from Kwiatkowski, Möhring and Spiesberger [11].

The aim of this write-up is to present the Monte Carlo event generator for the simulation of the deep inelastic scattering process $e^{\pm}p \to e^{\pm}(\gamma)X$ at HERA energies for the standard electroweak neutral current ($\gamma + Z^0$ exchange). In the calculation we include the real and virtual single-photon emission from the initial and final lepton states in the $\mathcal{O}(\alpha)$ QED. The present MC program is an upgrade of the previous version with collinear bremsstrahlung from the initial lepton state LESKO-C [8]. The program presented here is sufficient to describe the differential cross sections with a typical accuracy * of order of a few %. Owing to its flexibility, it may be a very convenient starting point for further refinements, such as the inclusion of higher-order radiative corrections of the electroweak theory.

In the following we briefly describe the MC algorithm and some basic concepts used in its development. The method of the MC generation, in general, is similar to the one described in ref. [8] **. The central variable, which is used in the MC algorithm is the momentum transfer squared Q^2, exchanged in the elementary electron–quark scattering process. Since the parton model is not valid for Q^2 below $\mathcal{O}(1)$ GeV^2 and the differential cross section is proportional to $1/Q^4$, we have to exclude from the MC the region of the phase space close to $Q^2 = 0$. It should be done at the early stage of the event generation, so that we avoid large contributions to the differential cross section from this region which makes no sense for the deep inelastic processes. The corresponding cutoff in the MC must be chosen in such a way that it is easy to realize it in the experiment. The cutoff which fulfils these requirements seems to be a minimum of the transverse momentum $p_{\mathrm{T,min}}$ of the final particles with respect to the beams. It guarantees Q^2 to be greater than some $Q^2_{\mathrm{min}} \approx p^2_{\mathrm{T,min}}$ and it naturally translates into the experimental cuts, for more details see ref. [14]. The program generates only events with a transverse momentum p_{T} of the final particles (quark/electron + photon) greater than $p_{\mathrm{T,min}}$ which is an input parameter.

For the complete description of the considered process one needs six (5 essential + 1 trivial) variables. Besides Q^2 we choose still the Bjorken variable x, two azimuthal angles ϕ, ψ and two variables z_1, z_2 corresponding to the photon emission from the initial and final leptonic states [15] (more details in the next section). The variables Q^2 and x are generated in the first step of the MC algorithm. The values of z_1 and z_2 are chosen together in the second step of the algorithm and this is done almost independently of the choice of Q^2 and x. The correlations between all these variables and the exact differential cross section for this process are introduced in the last stage of the MC algorithm by means of the rejection technique. Such a method may be efficiently used, because the differential cross section for the electron-quark t-channel exchange process $\mathrm{d}\sigma(s, t)/\mathrm{d}t$ is weakly dependent on s for fixed $t = -Q^2$. In the MC algorithm the above s-dependent is neglected in the first stage and it is restored later by means of rejection of some events.

The outline of this write-up is the following. In section 2 we give more details about the Monte Carlo algorithm for event generation. The structure of the program is described in section 3. In section 4 we explain how to use the program and section 5 contains some numerical results and final conclusions.

* To estimate the precision one has to perform the calculation of $\mathcal{O}(\alpha^2)$ corrections.

** It is perhaps worth to mention that the first version of LESKO-F with the same generation algorithm and kinematics was written already in 1987 and the following MC multi-photon generator BHLUMI [12,13] for small angle Bhabha scattering was based on this early version of the present program.

2. The Monte Carlo algorithm

The program simulates the deep inelastic electron–proton neutral current scattering process at HERA energies with single bremsstrahlung photon emission from the initial and final lepton states. The kinematics for such a process

$$l(p_1) + p(P) \to l(p_2) + \gamma(k) + X(P'), \quad l = e^{\pm}, \tag{1}$$

is depicted in fig. 1. It is assumed that the single bremsstrahlung photon with the four-momentum k is emitted from in/outgoing electrons (not from quarks). The four-momentum of the quark in the proton is denoted by $q_1 = xP$ and that of the final state quark (jet) by q_2.

In the partonic picture the cross section for the process (1) with regard to kinematic limits and cuts may be written in the following compact form

$$\begin{aligned} \sigma &= \int_{|t|_{\min}}^{s_0} \mathrm{d}|t| \int_0^{-1} \mathrm{d}x \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi} \int_0^1 \mathrm{d}z_1 \int_0^1 \mathrm{d}z_2 \int_0^{2\pi} \frac{\mathrm{d}\psi}{2\pi} \varrho(t, x, z_1, z_2, \phi, \psi), \\ \varrho(t, x, z_1, z_2, \phi, \psi) &= \sum_q \Theta(s_1 - s_{1,\min}(t))\, q_{\mathrm{q}}(x, t)\, \rho_{\mathrm{q}}(t, x, z_1, z_2, \phi, \psi), \end{aligned} \tag{2}$$

where

$$\begin{aligned} & s_0 = (p_1 + P)^2, \qquad t = -Q^2 = (p_1 - p_2 - k)^2, \\ & s_1 = (p_2 + q_2)^2, \qquad p_1^2 = p_2^2 = m_l^2, \qquad q_2^2 = m_{\mathrm{q}}^2, \\ & |t|_{\min} = \frac{2\left(s_0 p_{\mathrm{T,min}}^2 + M^2 m_q^2\right)}{s_0 - M^2 - m_q^2 + \left(\left(s_0 - M^2 - m_{\mathrm{q}}^2\right)^2 - 4M^2 m_{\mathrm{q}}^2\right)^{1/2}}, \\ & s_{1,\min}(t) = \frac{|t|\left(|t| + M^2 + m_{\mathrm{q}}^2\right) + M^2 m_{\mathrm{q}}^2}{|t| - p_{\mathrm{T,min}}^2}, \qquad M^2 = (k + p_2)^2 \end{aligned} \tag{3}$$

and $\rho_{\mathrm{q}}(t, x, z_1, z_2, \phi, \psi)$ is the differential cross section of the lepton–quark (lq) scattering including the single photon emission from the lepton line, where an index q denotes the quarks: u, d, c, s, $\bar{\mathrm{u}}$, $\bar{\mathrm{d}}$, $\bar{\mathrm{c}}$, $\bar{\mathrm{s}}$.

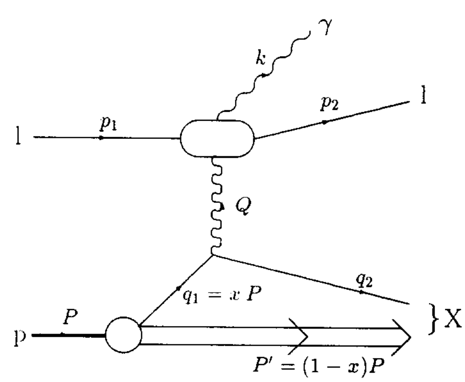

Fig. 1. Kinematics of the deep inelastic neutral current electron-proton scattering process including single-photon bremsstrahlung from the lepton line.

The variable ϕ in eq. (2) is a trivial azimuthal angle around the beam and ψ is the azimuthal angle defined in the rest frame of $k+p_2$ with respect to the plane defined by the incoming electron and outgoing quark momenta ($\boldsymbol{p}_1$, $\boldsymbol{q}_2$) with the third axis pointing in the direction of the incoming electron.

The last two variables used in the above formula are defined as follows

$$z_1 = \frac{2(kp_1)}{|t|+2(kp_2)}, \qquad z_2 = \frac{2(kp_2)}{|t|+2(kp_2)}. \tag{4}$$

The allowed range for the variables z_i almost coincides with the unit square $0 \le z_i \le 1$. More precisely, the z-variables have to satisfy

$$\delta_1(z_2) \le z_1 \le 1, \qquad \delta_2(z_1) \le z_2 \le 1, \tag{5}$$

where

$$\delta_1(z_2) = \frac{m_1^2}{|t|} z_2(1-z_2) \qquad \delta_2(z_1) = \frac{m_1^2}{|t|}\frac{z_1}{1-z_1}. \tag{6}$$

The essential property of these z-variables is that they have a rather simple meaning for hard collinear photon emission. For hard collinear emission from the initial electron state, z_2 is simply *the fraction of the incoming electron momentum carried by a hard collinear photon* ($z_1 \approx 0$). While for hard collinear emission from the final electron state z_1 is *the fraction of the momentum of the dissociating quasireal electron carried by a hard collinear photon* ($z_2 \approx 0$) [15].

In eq. (2) $q_q(x, t)$ is a distribution of the quark q in the proton. In the present version of the program we use several different quark distribution parametrization (for more details see section 3). Since the structure functions are formally treated in the MC program as arbitrary functions, so an inclusion of some other ones is rather straightforward.

The Θ-function in eq. (2) is derived from energy conservation and the requirement that the final quark (electron + photon) transverse momentum is at least $p_{\mathrm{T,min}}$. In the program there is also an option for the event generation above a certain minimum of momentum transfer $|t| \ge |t|_{\min}$. In this case in eq. (4) we set

$$s_{1,\min} = \left(|t|\left(|t|+M^2+m_q^2\right)+M^2m_q^2\right)/|t|.$$

From now on we always assume $|t| \gg m_1^2$, $p_1^2 = p_2^2 = m_1^2 = m^2$ and $q_1^2 = q_2^2 = 0$. It is possible because, due to p_{T}-cut, we restrict ourselves to deep inelastic scattering only.

Let us now discuss the treatment of the infrared singularity in the MC. In $\mathscr{O}(\alpha)$ QED we can divide the differential cross section $\rho_q(t, x, z_1, z_2, \phi, \psi)$ into two parts: one for the soft photon emission and another one for the hard photon emission

$$\rho_q = \delta(z_1)\ \delta(z_2)\rho_q^{\mathrm{soft}}(\Sigma) + \Theta(z_1/\epsilon_1 + z_2/\epsilon_2 - 1)\ \rho_q^{\mathrm{hard}}, \tag{7}$$

where the boundary Σ, defined by

$$\frac{z_1}{\epsilon_1} + \frac{z_2}{\epsilon_2} < 1, \tag{8}$$

separates the infrared singularity (for $z_1 = z_2 = 0$) from the phase space region for hard bremsstrahlung. The infrared singularity from real soft photon emission is canceled in the standard way be adding the virtual photonic contribution from the vertex correction (regularized by a finite photon mass) inside the boundary Σ. It can be easily verified that the boundary $z_1 + z_2 = \epsilon(\epsilon_1 = \epsilon_2 = \epsilon$ in (8)) corresponds to an ellipsoid in the space of c.m.s. photon momentum [15]. The boundary Σ should be sufficiently small so as to be as good as possible for the soft photon approximation. On the other hand it can not be too small because the "soft" contribution $\rho_{\mathrm{q}}^{\mathrm{soft}}(\Sigma)$ in (7) might become negative. It is no problem in numerical calculations but in a Monte Carlo approach, since $\rho_{\mathrm{q}}^{\mathrm{soft}}(\Sigma)$ has a definite probabilistic interpretation, it has to be positive *. We have found through a MC exercise that the choice of Σ with $\epsilon_1 = 10^{-4}$ and $\epsilon_2 = 10^{-3}$ may be applied. It means that the emitted photons with the energy above about 0.1 GeV in the HERA laboratory system are not distorted by this cut and it is acceptable by the experimental resolution requirements [9]. Although the "soft" and "hard" parts of the cross section separately depend on the choice of the boundary Σ, the sum of them should not depend on it. With help of the MC exercise we checked that the program satisfies this condition for the range $10^{-4} \le \epsilon_1 \le 10^{-2}$ and $10^{-3} \le \epsilon_2 \le 10^{-2}$.

The "soft" part for such a cut-off reads as follows

$$\rho_{\mathrm{q}}^{\mathrm{soft}}(t, x, \phi, \psi; \Sigma) = D_{\mathrm{lq}}(s, t)\Delta^{\mathrm{s}}(t; \Sigma), \qquad \Delta^{\mathrm{s}}(t; \Sigma) = 2\pi\delta(\psi)(1 + \delta_{\mathrm{soft}}(\Sigma)), \tag{9}$$

where

$$\delta_{\mathrm{soft}}(\Sigma) = \frac{\alpha}{\pi}\left[\left(\ln\frac{|t|}{m^2} - 1\right)\ln(\epsilon_1\epsilon_2) + \frac{3}{2}\ln\frac{|t|}{m^2} - \frac{1}{2}\ln^2\frac{\epsilon_1}{\epsilon_2} - \tfrac{1}{6}\pi^2 - 2\right] \tag{10}$$

and $D_{\mathrm{lq}}(s, t) = \mathrm{d}\sigma(s, t)/\mathrm{d}t$ is the differential cross section of lepton–quark scattering ($s = s_0 x$), given explicitly e.g. in ref. [8,14].

The "hard" part may be written as follows

$$\rho_{\mathrm{q}}^{\mathrm{hard}}(t, x, z_1, z_2, \phi, \psi) = \frac{\pi^4}{2}\frac{(|t| + M^2)^2}{s^2|t|}\left|\mathcal{M}_{\mathrm{q}}^{\mathrm{hard}}\right|^2 \Theta(z_1 - \delta_1(z_2))\, \Theta(z_2 - \delta_2(z_1)), \tag{11}$$

where $|\mathcal{M}_{\mathrm{q}}^{\mathrm{hard}}|$ in the above formula is the matrix element of the lepton–quark neutral current scattering with the single hard photon emission from the lepton line, taken originally from ref. [18] (see appendix). The Θ-functions in eq. (11) reflect the kinematic limits for this process.

Having defined all the ingredients in the master formula (2) we can now describe in more details the MC algorithm used to generate the differential distribution ϱ. A schematic diagram of this algorithm is depicted in fig. 2. The variables t, x, z_1, z_2, ϕ, ψ and the type of the scattered quark q are generated from top to bottom of the diagram. The return loop in this picture represents the rejection procedure in the MC algorithm. The rejection technique, in general, consists in replacing the distribution $\varrho(t, x, z_1, z_2, \phi, \psi)$ to be generated by the distribution $\varrho_1(t, x, z_1, z_2, \phi, \psi)$ which is simpler than ϱ and therefore easier to generate, but fulfilling the inequality $\varrho \le \varrho_1$ and being as close to ϱ as possible. In the first step we generate the distribution ϱ_1 and for each event we calculate the weight $w_1 = \varrho/\varrho_1$. This weight is then compared in the next step with a random number $r \in (0, 1)$ and if $r \le w_1$ the event is accepted, otherwise it is rejected and the procedure is repeated. This way, the accepted events are distributed according to the desired distribution ϱ.

We can obtain the distribution ϱ_1 by making the following replacement in eq. (2),

$$s_1 \to s_0 x, \tag{12}$$

and by simplifying somewhat the hard bremsstrahlung element $\mathcal{M}_{\mathrm{q}}^{\mathrm{hard}}$. The replacement (12) is possible due to the mild dependence of the differential cross section on s for fixed t, mentioned in the Introduction. This replacement enlarges a little the available phase space (see the Θ-function in eq. (2)).

* The real solution for the problem with the choice of the boundary Σ is to avoid it by the exponentiation [16,17].

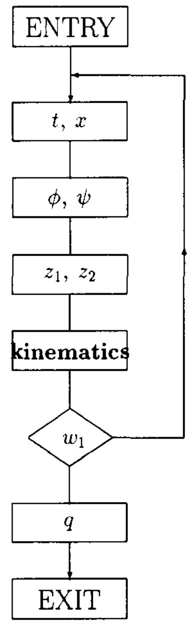

Fig. 2. Scheme of the Monte Carlo algorithm. Generation of the indicated variables and other operations are depicted by boxes and the return loop represents rejection of events.

The new distribution may be written as

$$\varrho_1(t, x, z_1, z_2, \phi, \psi) = \kappa\Theta(x - s_{1,\min}(t)/s_0)\ \Delta(t, z_1, z_2) \sum_q D_{\mathrm{lq}}(s_0 x, t)\ q_{\mathrm{q}}(x, t), \tag{13}$$

where

$$\Delta(t, z_1, z_2) = \delta(z_1)\delta(z_2)\ \Delta^{\mathrm{s}}(t; \Sigma) + \Theta(z_1/\epsilon_1 + z_2/\epsilon_2 - 1)\Delta^{\mathrm{h}}(t, z_1, z_2; \Sigma) \tag{14}$$

and

$$\Delta^{\mathrm{h}}(t, z_1, z_2; \Sigma) = \Theta(z_1 - \delta_1(z_2))\ \Theta(z_2 - \delta_2(z_1))\frac{\alpha}{\pi}\frac{1}{z_1 z_2}, \tag{15}$$

where $\Delta^{\mathrm{s}}(t; \Sigma)$ is defined in eq. (9). It is much simpler to generate the variables t, x, z_1, z_2 according to the distribution ϱ_1. After generation of these variables, the above simplification is corrected by rejection with the weight

$$w_1 = \varrho(t, x, z_1, z_2, \phi, \psi)/\varrho_1(t, x, z_1, z_2, \phi, \psi). \tag{16}$$

The dummy parameter κ is adjusted such that $w_1 \le 1$. For the basic process (1), a numerical experiment or an inspection of relevant formulae shows that for the HERA energies one may put $\kappa = 1.13$. But it may not be true for some nonstandard process and in such a case the program automatically adjusts κ using the first 500 generated events. The rejection rate appears to be reasonably small, usually less than 20%. The total cross section (2) may be estimated from the following relation

$$\sigma = \sigma_1 \langle w_1 \rangle, \tag{17}$$

where $\langle w_1 \rangle$ is the average weight taken over all accepted and rejected events, and the approximate cross section

$$\sigma_1 = \int \mathrm{d}|t|\, \mathrm{d}x\, \mathrm{d}z_1\, \mathrm{d}z_2\, \varrho_1(t, x, z_1, z_2, \phi, \psi)$$

$$= \kappa \int_{|t|}^{s_0} \mathrm{d}|t| \int_{s_{1,\min}/s_0}^{1} \mathrm{d}x \sum_q q_q(t, x)\; D_{\mathrm{lq}}(s_0 x, t) \int_0^1 \mathrm{d}z_1 \int_0^1 \mathrm{d}z_2\; \Delta(t, z_1, z_2) \tag{18}$$

has to be calculated. A very important advantage of the above simplification is that the generation of the variables t, x may be achieved independently of z_1, z_2. This is possible because $\int_0^1 \Delta(t, z_1, z_2) \approx 1$ *. The variables t, x are generated according to the distribution

$$f(t, x) = \sum_q q_q(t, x)\; D_{\mathrm{lq}}(s_0 x, t) \tag{19}$$

using a two-dimensional MC sampler VESKO2, the same as in the program LESKO-C. It sets up, in an initialization mode, a grid of cells which is denser in region where $f(t, x)$ is higher and less dense in the rest of the integration domain. In a procedure of generating pairs (t, x), first a cell is randomly chosen and then the pair (t, x) is generated within the cell (by means of rejection) precisely according to the distribution $f(t, x)$. The generation method is rather efficient, even for almost arbitrary parton distribution functions $q_q(t, x)$. Apart from the generation of the variables t and x this sampler yields also the value of the integral $\int \mathrm{d}t\, \mathrm{d}x\, f(t, x)$ with a good precision. It is needed to evaluate the total cross section σ according to (17).

The variables z_1, z_2 are generated according to the distribution $\Delta(t, z_1, z_2)$ when t is already known. This generation is rather easy to perform and for more details we refer the reader to the source code. For a complete set of the phase space variables necessary to describe the event one needs in addition two defined above azimuthal angles ϕ and ψ. They are generated uniformly in the range $(0, 2\pi)$.

Having all the kinematical variables chosen we are able to calculate the value of the distribution $\varrho(t, x, z_1, z_2, \phi, \psi)$ which contains summed contributions from all the quark flavours, and then we can generate the type of the hit quark q according to the probability

$$p_q = q_q(x, t)\; \rho_q(t, x, z_1, z_2, \phi, \psi) / \varrho(t, x, z_1, z_2, \phi, \psi). \tag{20}$$

Using the variables t, x, z_1, z_2, ϕ, ψ and the quark flavour index q one can construct all the momenta and flavours of the particles in the final state.

3. The structure of the program

The structure of this program is in general similar the structure of the program LESKO-C, described in ref. [8]. The program is divided into three distinct parts (LESF, LESLIB, PDFMIN) which accomplish different functional tasks. The main routine of the program is called LESKO. It is placed in the part named LESF. This routine has to be called by the user in order to generate events. It administers input/output, initializes subprograms and prints some final results. It is described in more details in the next section. The basic MC algorithm, described in the previous section, is implemented in the subroutine DZIDZA. It is called in LESKO and is located in the part LESF. This part contains also subprograms for the calculation of the matrix element and the kinematics of the process (1). Utility

* In fact, this integral depends weakly on t and we replace it by $\Delta_1 = \Delta/(1 + f(t))$ for which $\int_0^1 \mathrm{d}z_1\, \mathrm{d}z_2\, \Delta_1 = 1$, where $0 < f(t) < 0.13$.

subprograms such as a random number generator, the two-dimensional MC sampler VESKO2 and subprograms for Lorentz transformations are concentrated in the second part, named LESLIB. The program includes an interface to the package PAKPDF of parton distribution functions parametrizations [19–25,26] described in ref. [27]. In the program deck we enclose a small version of this package, named PDFMIN, with only two parametrization [19,23], but one may easily use the original package without any change of the program.

The heart of the whole program is the subroutine DZIDZA. It provides the elementary phase space variables t, x, z_1, z_2, ϕ, ψ according to the MC algorithm described in section 2 and calculates the four-momenta of all final state particles. The generation of the variables is performed in the following subprograms: t, x in VESKO2, q in FLAPIK and z_1, z_2 in BREMSS. The distributions ϱ, defined in eq.(2), and ϱ_1, defined in eq. (13), are calculated by the function ROMS: first by calling the function BSMATE and second by calling the function BSMATR. The differential cross section D_{lq} for the electron–quark neutron current scattering is provided by the function DISTNC. The values of the quark distribution functions in the proton $q_{\mathrm{q}}(t, x)$ are calculated, for a given t and x, in the routine QUAKER and stored in the common block LEFLAV. One may use various parametrizations of these distributions by calling appropriate subprograms in QUAKER. After all the basic space variables t, x, z_1, z_2, ϕ, ψ have been generated, the four-momenta k, p_2, q_2, P' of all final partons (see fig. 1) are calculated in the routine KINO2 called from DZIDZA. In this version of the program we use the switchable random number generator called VARRAN; the user may choose among two good quality random number generators RANMAR [28] and RANECU [29] using the switch KEYRND in the routine LESKO (KEYRND = 1, 2 for RANMAR and RANECU, respectively). RANMAR is the default random number generator. It is initialized automatically in the first call to the program but it can be initialized or restarted by the user as well (for details see the routines MARRAN and/or RANECU in the part LESLIB).

4. How to use the program

A Monte Carlo event, i.e. a complete set of final momenta and flavours, is generated by a single call to the subroutine LESKO. For example a complete sequence of calls which generates 1000 events may look like

```
    REAL*4 XPR(10)
    INTEGER*4 IDPROC,INLEPT,NPR(10)
    define histograms,IDPROC,INLEPT,NPR(10),XPR(10)
    CALL LESKO (-1, IDPROC,INLEPT,NPR,XPR)
    DO 500 IEVENT=1,1000
    CALL LESKO(0,IDPROC,INLEPT,NPR,XPR)
    fill histograms
500 CONTINUE
    CALL LESKO(1,IDPROC,INLEPT,NPR,XPR)
    print histograms and other final results
```

At it is obvious from the above example the first integer parameter MODE in any CALL LESKO(MODE,...) simply decides whether LESKO is called in initialization mode (MODE = −1), generation mode (MODE = 0) or post generation mode (MODE = 1). The first call (obligatory) is employed in order to transfer the input data through LESKO parameters and to execute initializations in subprograms (no event generation), the second one in order to generate a MC event, and the third call (optional) terminates generation by printing some useful output and calculating the total integrated cross

Table 1
Steering parameters of LESKO-F.

Parameter	Meaning
IDPROC	Process identifier, IDPROC = 1 denotes the neutral process ep → eX with $\gamma + Z^0$ exchange in t channel (other processes may be added in the future).
INLEPT	Flavour identifier of the lepton beam, INLEPT = 11, −11 denotes electron and positron, respectively.
NPR(1) = KEYRAD	Switch for QED bremsstrahlung. KEYRAD = 1,0 for bremsstrahlung switched on, off.
NPR(2) = KEYTRG	For KEYTRG = 1 events are produced with a minimum transverse momentum of outgoing particles (quark/electron + photon) $p_{T,\min}$ = PTMIN or for KEYTRG = 0 with a minimum momentum transfer $\sqrt{Q^2_{\min}}$ = PTMIN (this option makes sense for KEYRAD = 0 only).
NPR(3) = KEYVAL	For KEYVAL = 1,0 the contribution from valence quarks is switched on, off (for tests only).
NPR(4) = KEYSEA	For KEYSEA = 1,0 the contribution from sea quarks is switched. on, off (for tests only).
NPR(5) = KEYPDF	This switch decides which of the parametrizations from the package of parton distribution functions is chosen. In the present version of the program with the small package PDFMIN allowed values of KEYPDF are 0,1,5 (for the complete PDF-package of ref. [27] KEYPDF = 0–8), see also comments at the beginning of the subroutine LESKO.
NPR(6) = KEYGSW	For KEYGSW = 0 neither γ nor Z^0 self energies are included. For KEYGSW = 1 the complete set of the vacuum polarization functions from the electroweak standard model is included (this option is recommended).
NPR(7) = KEYSET	It specifies one of the sets in the individual parametrization of parton distribution functions. The values allowed for KEYSET depend on the chosen parametrization (KEYPDF) and they are described in details in ref. [27] (see also the source code).
XPR(1) = ENELE	Energy of the lepton beam (GeV).
XPR(2) = ENPRO	Energy of the proton beam (GeV).
XPR(3) = PTMIN	Minimum transverse momentum $p_{T,\min}$ (GeV) of the produced quark (lepton + photon) or $\sqrt{Q^2_{\min}}$ for KEYTRG = 0. The minimal value allowed for PTMIN is about 1.0 (GeV); for the lower values the parton model may be not valid.
XPR(4) = POLAR	Longitudinal spin polarization of the lepton beam. POLAR ∈ (+1.0, 1.0); POLAR = 0.0 for the unpolarized beam.

section corresponding to a generated sample. Other output results, as e.g. four-momenta and flavours of the final state, are afforded by appropriate common blocks, see later in this Section.

Let us now give more details about the steering parameters of LESKO and the particular modes.

4.1. Initialization mode

The input data set, transferred to LESKO in the initialization mode (MODE = −1), is listed in the table 1. The integer IDPROC is the variable used to define the type of the scattering process and the integer INLEPT is a flavour identifier for the $e^{\pm}$ beam (INLEPT = 11, −11 for electrons and positrons, respectively). The $e^{\pm}$ beam is assumed to be directed along the third axis in the laboratory system and the proton beam opposite to it. The other parameters are collected in arrays NPR(10) and XPR(10); for more details see table 1. Some parameters, as e.g. useful constants and particle masses, are provided by the subroutine PARLES called in LESKO.

4.2. Event generation mode

In the event generation mode, i.e. for MODE = 0, all other arguments of the subroutine LESKO are ignored and a Monte Carlo event is produced according to the algorithm described in section 2. For each event LESKO-F provides momenta and flavours of final particles on the parton level only (no quark fragmentation is performed). The momenta may be found in the REAL*8 common block UTIL8 or its REAL*4 version UTIL4. The first one reads as follows:

```
COMMON/UTIL8/PELE(4),PQUA(4),PHOT(4),PROH(4),DEEL,DEPR
```

where REAL*8 PELE, PQUA are four-momenta of the outgoing lepton $l = e^{\pm}$ and of the scattered quark q′ (i.e. p_2 and q_2 respectively, see fig. 1), and REAL*8 PHOT is the momentum of the bremsstrahlung photon (i.e. k in fig. 1) while REAL*8 PROH is the four-momentum of the proton remnant (i.e. P'), all in units of GeV. REAL*8 DEEL and DEPR are energies (in GeV) of the electron and proton beams, respectively. The flavour of the struck quark is stored in the INTEGER*4 common block

```
COMMON/FLASC/LAVAL,IDQUA
```

LAVAL = 1, 0 says whether a valence (LAVAL = 1) or sea (LAVAL = 0) quark was struck off the photon while IDQUA is the identifier of this quark according to the PDG convention [30] (see also comments in the source code of the subroutine LESKO).

Apart from it each event is stored in the standardized HEPEVT event record [31]. To specify particles, a numbering scheme developed by the Particle Data Group [30] is employed. (Note: Since the proton remnant is a nonstandard object the PDG code for it we set to 81).

The minimum requirement to achieve a significant result is to set up the steering parameters of the program according to table 1.

4.3. Postgeneration mode

A call to LESKO in this mode (MODE = 1) may be optionally used in order to obtain the value of the integrated cross section σ_t and the number of generated event. The cross section σ_t is obtained with a statistical error depending on the number of generated events. All this information is printed in the output file and it is also provided to the user through the parameter arrays XPR and NPR; see table 2.

5. Some numerical results and final conclusions

The program deck comprises a demonstration main program DEMOLF which includes an example for the use of the program. Sample test output at the end of paper includes results from running the above demonstration program. It includes: print-out from LESKO-F before and after event generation and a list of four-momenta for a few first events.

Table 2
Some output results

Parameter	Meaning
NPR(1)	Number of generated events.
XPR(1)	Integrated total cross section σ_t in units of nanobarn.
XPR(2)	Relative error estimate of σ_t in per cent.

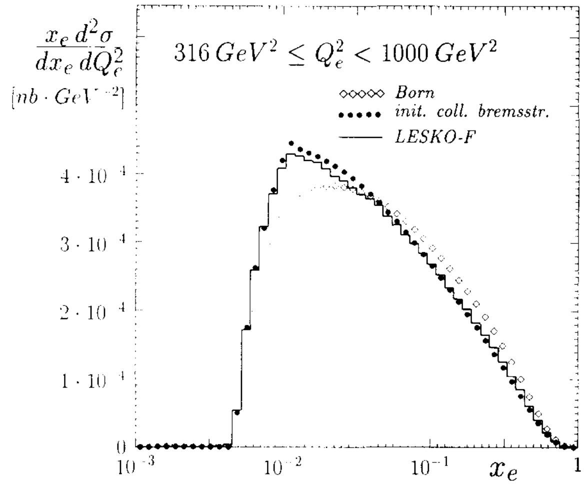

Fig. 3. Distributions of differential cross section $x_e\ \mathrm{d}^2\sigma/\mathrm{d}x_e\ \mathrm{d}Q_e^2$ obtained from LESKO-F (solid line) and from non-Monte Carlo calculations: in the Born approximation (◇◇◇) and in the collinear bremsstrahlung approximation (●●●) (see section 5).

An example of the numerical results obtained from LESKO-F is presented in fig. 3. It shows the distribution $x_e\ \mathrm{d}^2\sigma/\mathrm{d}x_e\ \mathrm{d}Q_e^2$ acquired by the use of LESKO-F (solid line in fig. 3) in comparison to the results of non-Monte Carlo calculations: in the Born approximation (small diamonds) and in the leading logarithmic approximation for initial electron state bremsstrahlung (small filled circles). As one can see in the figure the bremsstrahlung cross section exceeds considerably the Born cross section in the region of small x_e. This effect is of kinematical origin and corresponds to the hard photon emission from the initial electron state. For higher x_e the bremsstrahlung cross section becomes lower than the Born cross section due to the negative contribution from the soft bremsstrahlung (for more details about these effects see e.g. ref. [6]). The results of LESKO-F are in agreement on the level of a few percent with ones for the leading logarithmic approximation. These distributions were obtained for a transverse momentum of the final quark greater than $p_{\mathrm{T,min}} = 10$ GeV and for the momentum transfer squared 316 GeV$^2 < Q_e^2 \leq 1000$ GeV^2. For these MC simulations and numerical calculations we used the proton structure functions from Duke and Owens [19]. Since the $p_{\mathrm{T,min}}$ cutoff is the steering parameter of the program, it enables to cover effectively various regions of the (x, Q^2) space. The efficiency of the program for the event generation does almost not depend on the value of $p_{\mathrm{T,min}}$.

Recent results of the comparison between LESKO-F and the Monte Carlo program HERACLES [11], show a good agreement of the two generators.

Let us conclude our paper with a few remarks about further development of the LESKO-F Monte Carlo event generator:

• The program presented in this paper includes the bremsstrahlung effects of $\mathcal{O}(\alpha)$ approximation. The conservative estimate of the overall precision of our program is a few percent (numerical precision and QED higher orders). It could be improved by additional tests sensitive to corrections of order α/π and the inclusion of the second-order leading-logarithmic corrections of order $((\alpha/\pi)\ \ln(Q^2/m_e^2)^2$ which are of the same size as non logarithmic α/π corrections.

• The most effective method of including higher-order corrections is the exponentiation of the soft–photon contributions. In some parts of the phase space this is a necessity (see ref. [4]). A Monte Carlo algorithm for exponentiation in the process with t-channel exchange is available [12,13,32] for low angle Bhabha scattering.

• The present version of the program does not include the hadronization as well as QCD radiative effects. This is, however, rather important from the experimental point of view and should be done in the near future *.

• The next thing that can be done is the inclusion of a longitudinal structure function which is interesting for a gluon distribution measurements [34,35].

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Appendix. The hard bremsstrahlung matrix element

The matrix element for the elementary electron (positron)–quark neutral current scattering process including the single hard photon emission from the lepton line

$$\mathrm{e}(p_1) + \mathrm{q}(q_1) \to \mathrm{e}(p_2) + \mathrm{q}(q_2) + \gamma(k) \tag{21}$$

reads as follows [18]

$$\left|\mathcal{M}_{\mathrm{q}}^{\mathrm{hard}}\right|^2 = \left|\mathcal{M}_{\mathrm{q}}^{\mathrm{hard}}\right|^2_{\mathrm{ml}} + \left|\mathcal{M}_{\mathrm{q}}^{\mathrm{hard}}\right|^2_{\mathrm{dp}}, \tag{22}$$

where

$$\left|\mathcal{M}_{\mathrm{q}}^{\mathrm{hard}}\right|^2_{\mathrm{ml}} = \frac{\alpha^3}{8\pi^4} \sum_{i,j=\gamma,Z} \left(\left[A_{\mathrm{q}}^{ij}\left(s^2+s_1^2+u^2+u_1^2\right) + B_{\mathrm{q}}^{ij}\left(s^2+s_1^2-u^2-u_1^2\right)\right] \right.$$
$$\left. \times Q_{\mathrm{e}}^2 \frac{-t}{(kp_1)(kp_2)} P_i(t)\ P_j(t) \right) \tag{23}$$

is the matrix element for massless spinors and

$$\left|\mathcal{M}_{\mathrm{q}}^{\mathrm{hard}}\right|^2_{\mathrm{dp}} = \frac{\alpha^3}{4\pi^4} \sum_{i,j=\gamma,Z} \left\{ -Q_{\mathrm{e}}^2 m_{\mathrm{e}}^2 P_i(t)\ P_j(t) \left[A_{\mathrm{q}}^{ij}\left(\frac{s_1^2+u_1^2}{(kp_1)^2} + \frac{s^2+u^2}{(kp_2)^2} \right) + B_{\mathrm{q}}^{ij}\left(\frac{s_1^2-u_1^2}{(kp_1)^2} + \frac{s^2-u^2}{(kp_2)^2} \right) \right] \right\} \tag{24}$$

is the correction from the finite mass of spinors (see ref. [18]).

* The first version of the program including parton cascades and fragmentation, named FRANEQ, which follows the old Lund convention of JETSET 6.3 [33] has recently been developed by W. Płaczek. It can be obtained by e-mail from H1KPLA@DH-HDESY3.

In the above equations

$$\begin{aligned} s &= (p_1+q_1)^2, & t &= (q_1-q_2)^2, & u &= (p_1-q_2)^2, \\ s_1 &= (p_2+q_2)^2, & t_1 &= (p_1-p_2)^2, & u_1 &= (p_2-q_1)^2. \end{aligned} \tag{25}$$

The factors A_{q}^{ij} and B_{q}^{ij} in eqs. (23) and (24) are combinations of fermion–boson coupling constants for the neutral electroweak currents

$$A_{\mathrm{q}}^{ij} = \left(\lambda_{\mathrm{V}}^{\mathrm{e}ij} - \epsilon\lambda_{\mathrm{A}}^{\mathrm{e}ij}\right)\lambda_{\mathrm{V}}^{\mathrm{q}ij}, \qquad B_{q}^{ij} = \left(\lambda_{\mathrm{A}}^{\mathrm{e}ij} - \epsilon\lambda_{\mathrm{V}}^{\mathrm{e}ij}\right)\lambda_{\mathrm{A}}^{\mathrm{q}ij}, \tag{26}$$

where ϵ is the longitudinal spin polarization of the initial lepton while the quark is assumed to be unpolarized, and

$$\lambda_{\mathrm{V}}^{\mathrm{q}ij} = 2\left(v_{\mathrm{q}}^{i}v_{\mathrm{q}}^{j} - a_{\mathrm{q}}^{i}a_{\mathrm{q}}^{j}\right), \qquad \lambda_{\mathrm{A}}^{\mathrm{q}ij} = 2\left(v_{\mathrm{q}}^{i}a_{\mathrm{q}}^{j} - a_{\mathrm{q}}^{i}v_{\mathrm{q}}^{j}\right). \tag{27}$$

The quantities

$$v_{\mathrm{q}}^{\gamma} = Q_{\mathrm{q}}, \qquad a_{\mathrm{q}}^{\gamma} = 0, \qquad v_{\mathrm{q}}^{\mathrm{Z}} = \frac{I_{\mathrm{q}}^{3} - 2s_{\mathrm{W}}^{2}Q_{\mathrm{q}}}{2s_{\mathrm{W}}c_{\mathrm{W}}}, \qquad a_{\mathrm{q}}^{\mathrm{Z}} = \frac{I_{\mathrm{q}}^{3}}{2s_{\mathrm{W}}c_{\mathrm{W}}} \tag{28}$$

are the coupling constants, where Q_{q} and I_{q}^{3} are electric charge and projection of the weak isospin of the corresponding fermion $q_{\mathrm{L,R}}$ and s_{W}, c_{W} are sine and cosine of the weak mixing angle θ_{W}, respectively [36].

The $P_{i,j}(t)$ in the formulae (23) and (24) are the γ and Z^0 propagators defined by

$$P_{\gamma}(t) = \frac{1}{t\left(1 + \Pi_{\gamma\gamma}(t)\right)}, \qquad P_{\mathrm{Z}}(t) = \frac{1}{t - M_{\mathrm{Z}}}, \tag{29}$$

where M_{Z} is the Z^0 boson mass and $\Pi_{\gamma\gamma}(t)$ is the photon vacuum polarization function of the standard electroweak theory. The inclusion of this function corresponds effectively to taking the running coupling constant for the photon, i.e.

$$\alpha(t) = \alpha(0)F_{\mathrm{A}}(t), \tag{30}$$

and

$$F_{\mathrm{A}}(t) = \frac{1}{1 + \Pi_{\gamma\gamma}(t)}, \tag{31}$$

where the leptonic part of $\Pi_{\gamma\gamma}(t)$ is taken from ref. [37] and the hadronic one is calculated using a dispersion relation from ref. [38]. The self energy correction to the Z^0 propagator is rather small in the HERA range [5] and it is not necessary to include it with all details. A good approximation for this correction is achieved by incorporating to the Z^0 coupling constant the corrections to μ decay (see e.g. refs. [4–6]). In the program this is done as follows. The mixing angle θ_{W} is defined by the Z^0 and W masses [36], where the Z^0 mass M_{Z} is considered as an input parameter and the W mass M_{W} is calculated using the muon decay constant including the radiative corrections, as in ref. [4] *. Such a treatment of the corrections to the electroweak propagators yields a sufficient precision for the HERA experiments.

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TEST RUN OUTPUT

```
***********************************************************************
*            -------DEMOLE------------------------------              *
*          5000       NUMBER OF EVENTS TO BE GENERATED                *
***********************************************************************

***********************************************************************
*                     LESKO-F VERSION 2.2                             *
*              TO BE PUBLISHED IN COMP. PHYS. COMM.                   *
*                 AUTHORS: S. JADACH & W. PLACZEK                     *
*               ----------- INPUT PARAMETERS --------------           *
*                 1      =IDPROC,  PROCESS TYPE IDENT                 *
*                11      =INLEPT,  INITIAL LEPTON BEAM IDENT          *
*        30.0000000      =ENELE,   LEPTON   BEAM  (GEV)               *
*       820.0000000      =ENPRO,   PROTON   BEAM  (GEV)               *
*       98400.00000      =SSO,     TOTAL CMS ENERGY SQ. (GEV**2)      *
*        10.0000000      =PTMIN,   MINIM. PT OF Q (GEV)               *
*         0.0000000      =POLAR,   LEPTON BEAM SPIN POLARIZATION      *
*                 1      =KEYRND,  SWITCH FOR RAND. NUMB. GENER.      *
***********************************************************************

***********************************************************************
*              KEYS ARE SET AS FOLLOWS...                             *
*                 1      =KEYRAD,  RADIATION KEY                      *
*                 1      =KEYTRG,  PT**2 TRIGGER                      *
*                 1      =KEYVAL,  VALENCE QUARK ON/OFF               *
*                 1      =KEYSEA,  SEA     QUARK ON/OFF               *
*                 1      =KEYPDF,  PARAM. OF STRUCTURE FUNCTIONS      *
*                 1      =KEYSET,  SET IN THE PDF-PARAMETRIZ.         *
*                 1      =KEYGSW,  GSW RAD. CORR. ON/OFF              *
***********************************************************************

***********************************************************************
*              GSW PARAMETERS....                                     *
*    91.170000000000     = MASS OF ZO BOSON (GEV)                     *
*    80.002998888627     = MASS OF W  BOSON (GEV)                     *
*     0.229968265260     = SIN(THETAWEINB)**2                         *
***********************************************************************

MARran INITIALIZED: IJ,KL,IJKL,NTOT,NTOT2= 1802  9373  54217137  0  0


                     MOMENTA FROM LESKO,   EVENT NO.     1
           P(1)        P(2)        P(3)        P(4)       MASS
PELE    -9.25375    10.31136    24.62802    28.25766    0.00051
PQUA    10.32732   -11.50967  -122.24783   123.22199    0.00000
PHOT    -1.07357     1.19831     2.85929     3.28086    0.00000
PROH     0.00000     0.00000  -695.23949   695.23949    0.00000
SUM      0.00000     0.00000  -790.00000   850.00000

                     MOMENTA FROM LESKO,   EVENT NO.     2
           P(1)        P(2)        P(3)        P(4)       MASS
PELE    -8.73497    -5.87697    24.23202    26.42025    0.00051
PQUA     8.94727     6.01275    -3.09086    11.21428    0.00000
PHOT    -0.21229    -0.13579     0.58622     0.63809    0.00000
PROH     0.00000     0.00000  -811.72738   811.72738    0.00000
SUM      0.00000     0.00000  -790.00000   850.00000
```

```
                 MOMENTA FROM LESKO,   EVENT NO.     3
          P(1)       P(2)       P(3)       P(4)       MASS
PELE    4.40662    9.53864   20.85434   23.35182    0.00051
PQUA   -4.40662   -9.53864    4.40177   11.39208    0.00000
PHOT    0.00000    0.00000    0.00000    0.00000    0.00000
PROH    0.00000    0.00000 -815.25611  815.25611    0.00000
SUM     0.00000    0.00000 -790.00000  850.00000

                 MOMENTA FROM LESKO,   EVENT NO.     4
          P(1)       P(2)       P(3)       P(4)       MASS
PELE    8.47237  -16.10409   26.93559   32.50613    0.00051
PQUA   -8.47729   16.11332 -316.11552  316.63943    0.00000
PHOT    0.00493   -0.00923    0.01559    0.01878    0.00000
PROH    0.00000    0.00000 -500.83566  500.83566    0.00000
SUM     0.00000    0.00000 -790.00000  850.00000

                 MOMENTA FROM LESKO,   EVENT NO.     5
          P(1)       P(2)       P(3)       P(4)       MASS
PELE   -3.50258  -16.46261   26.48575   31.38121    0.00051
PQUA    3.50258   16.46261  -65.33775   67.47078    0.00000
PHOT    0.00000    0.00000    0.00000    0.00000    0.00000
PROH    0.00000    0.00000 -751.14800  751.14800    0.00000
SUM     0.00000    0.00000 -790.00000  850.00000


***********************************************************************
*                    DZIDZA  REPORTS:                                 *
*                5764     NUMBER OF RAW EVENTS                        *
*                5000     NUMBER OF ACCEPTED EVENTS                   *
*                   0     NUMBER OF OVERWEIGHTED EVENTS               *
*            1.130000     MAXIMUM WEIGHT                              *
*     0.452005765E+01     SIGMA TOTAL (NANOBARNS)                     *
*            0.406403     ERROR ON SIGMA TOTAL ( PERCENT )            *
*        0.150000E+32     ASSUMED LUMINOSITY CM**(-2)*SEC**(-1)       *
*        0.585799E+04     EVENT RATE PER DAY                          *
***********************************************************************
```