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MAJOR 1.3
A MONTE CARLO GENERATOR FOR HEAVY MAJORANA NEUTRINOS IN ELECTRON-PROTON COLLISIONS

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Abstract: The Monte Carlo generator MAJOR 1.3 simulates the production and decay of heavy Majorana neutrinos via lepton mixing, i.e. $e^-p \to NX \to e^\pm W^\mp X$ or $\nu_e ZX$. The process proceeds through normal charged current exchange in deep inelastic scattering. Physics and programming aspects are described in this manual.

Program summary:

Program name and version:	MAJOR version 1.3
Date of last version:	Dec 4, 1993
Purpose of program:	See abstract above
Program size:	1449 lines
Authors:	J. Rathsman, G. Ingelman (Rathsman@tsl.uu.se, Ingelman@vxdesy.desy.de)
Programming language:	Standard FORTRAN 77
Computer types:	Has run on VAX, IBM, DEC-station, hp and SGI
Input files needed:	Steering program
Other programs called:	LEPTO 6.1 and JETSET 7.3
Initial parton shower:	Available
Final parton shower:	Available
Fragmentation Model:	Lund string
QED radiative corrections:	Not included

1 Physics of included processes

The standard model of electroweak and strong interactions has been remarkably successful in describing the experimental data. Nevertheless, it cannot be the ultimate theory due to its theoretical shortcomings, *e.g.* for the understanding of the mass and family structure of quarks and leptons and the many free parameters. Attempts to solve the theoretical problems of the standard model have been made based on various theoretical grounds and several extended theories have been suggested and studied in detail. These theories are normally based on some larger symmetry group which unifies the interactions and is spontaneously broken down to the standard model gauge group. Particular attention has been given to models with an additional $U(1)$ symmetry or with left-right symmetry in the form $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, which can both be subgroups of the unification groups $SO(10)$ and E_6. The questions of neutrino masses and lepton number violation, which are of general importance (for a review see [Moh91]), enter explicitly in this context and, in particular, heavy Majorana neutrinos may be present [Buc91].

The simplest process, in terms of minimal new physics assumptions, to produce heavy Majorana neutrinos in *ep* collisions is through normal charged current interactions as illustrated in Fig. 1. The cross-section is suppressed, not only by limited phase space due to the large neutrino mass m_N, but also by the required mixing ξ between light and heavy Majorana neutrinos [Buc91, Buc92]. The light Majorana neutrinos can be identified with the normal neutrinos ν_e, ν_μ and ν_τ, whose small masses is naturally explained through the see-saw mechanism. The mixing in the leptonic part of the charged current interaction is given by a unitary Kobayashi-Maskawa type matrix V and the matrix ξ. A power series in ξ gives the connection between the weak eigenstates ν_L, ν_R and the Majorana mass eigenstates ν, N [Buc91], *i.e.*

$$\nu_L = \frac{1-\gamma_5}{2}(\nu + \xi N + \ldots)\,, \quad \nu_R = \frac{1+\gamma_5}{2}(N - \xi^T \nu + \ldots). \tag{1}$$

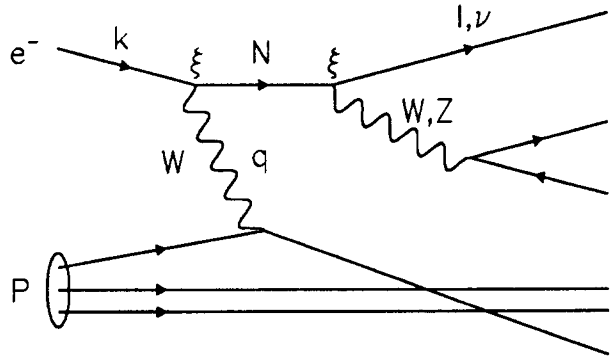

Figure 1: *Production (in ep collisions) and decays of heavy Majorana neutrinos.*

The heavy Majorana neutrinos will decay into either $\nu_\ell Z^0$, $\ell^+ W^-$ or $\ell^- W^+$ where the weak bosons can be taken as being on-shell since we only consider Majorana neutrino masses above the boson masses ($m_N > m_B$) due to mass limits [Ing93]. Using the narrow width approximation for the heavy Majorana neutrino propagator in Fig. 1, the cross-section for the process $e^- p \to NX$ where $N \to \ell^\pm W^\mp$ or $N \to \nu_\ell Z^0$ is [Buc91]

$$\begin{aligned}\frac{d\sigma}{dx\,dy\,dp_{\ell\perp}\,dy_\ell} &= \frac{G_F^3 m_W^6 |(V\xi)_{eN}|^2}{32\sqrt{2}\pi^3 \hat{s} m_N \Gamma_N} \frac{1}{(y\hat{s} + m_W^2)^2} \frac{1}{m_{N\perp}} \\ &\times \left[\cosh(y_N - y_\ell) - \frac{m_N^2 - m_B^2 - 2p_{\ell\perp}p_{N\perp}}{2m_{N\perp}p_{\ell\perp}}\right]^{-1/2} \\ &\times \left[\frac{m_N^2 - m_B^2 + 2p_{\ell\perp}p_{N\perp}}{2m_{N\perp}p_{\ell\perp}} - \cosh(y_N - y_\ell)\right]^{-1/2} \\ &\times \left\{A \cdot \left[u(x,\mu^2) + c(x,\mu^2)\right] + B \cdot \left[\bar{d}(x,\mu^2) + \bar{s}(x,\mu^2)\right]\right\}\end{aligned} \tag{2}$$

The independent variables are chosen as the normal deep inelastic scaling variables x and y together with the transverse momentum $p_{\ell\perp}$ and rapidity y_ℓ of the final state lepton ℓ from the Majorana neutrino decay. With four-momenta as in Fig. 1, $s=(P+k)^2$, $\hat{s}=xs$, $W^2=(P+q)^2$ and $Q^2=-q^2$. As usual, $x=Q^2/2P\cdot q$ and $y=P\cdot q/P\cdot k$, but they are globally constrained to $\frac{m_N^2}{s}\leq x\leq 1$ and $0\leq y\leq 1-\frac{m_N^2}{\hat{s}}$. The phase space is given by

$$\frac{1}{s}\left(p_{N\perp}^{min}+m_{N\perp}^{min}\right)^2 \leq \quad x \quad \leq 1 \tag{3}$$

$$\frac{\hat{s}-m_N^2-\sqrt{(\hat{s}-m_N^2)^2-4\,\hat{s}\,p_{N\perp}^{min\,2}}}{2\,\hat{s}} \leq \quad y \quad \leq \frac{\hat{s}-m_N^2+\sqrt{(\hat{s}-m_N^2)^2-4\,\hat{s}\,p_{N\perp}^{min\,2}}}{2\,\hat{s}} \tag{4}$$

$$0\leq \quad p_{\ell\perp} \quad \leq \frac{m_N^2-m_B^2}{2m_N^2}\sqrt{s} \tag{5}$$

$$\frac{m_N^2-m_B^2-2p_{\ell\perp}p_{N\perp}}{2m_{N\perp}p_{\ell\perp}} \leq \quad \cosh(y_N-y_\ell) \quad \leq \frac{m_N^2-m_B^2+2p_{\ell\perp}p_{N\perp}}{2m_{N\perp}p_{\ell\perp}} \tag{6}$$

The indices N and W denote the Majorana neutrino and the W boson exchanged in the t-channel, whereas B and ℓ denote the weak boson and lepton from the Majorana neutrino decay, respectively. The symbols y_ℓ, y_N, m, $m_\perp=\sqrt{m^2+p_\perp^2}$ and $p_\perp$ refer to rapidity, mass, transverse mass and transverse momentum, respectively. All frame dependent quantities are understood to be in the lab frame. Γ_N is the total width of the Majorana neutrino and the functions u, c, $\bar{d}$ and $\bar{s}$ are the parton density functions in the proton evaluated at a suitable scale μ.

The coefficient functions A,B depend on the decay products of the Majorana neutrino and are for the charged decays given by [Buc91]

$$\begin{aligned} A(\ell^-W^+) &= |(V\xi)_{\ell N}|^2\frac{4\hat{s}}{m_W^2} \\ &\quad \left[(m_N^2-m_W^2)(2m_W^2\hat{s}-m_N^4)-2m_N^2(2m_W^2-m_N^2)p_{\ell\perp}(xE_pe^{-y_\ell}+E_ee^{y_\ell})\right] \end{aligned} \tag{7}$$

$$\begin{aligned} B(\ell^-W^+) &= |(V\xi)_{\ell N}|^2\frac{8(\hat{s}(1-y)-m_N^2)}{m_W^2} \\ &\quad \left[\hat{s}(1-y)m_W^2(m_N^2-m_W^2)-m_N^2(2m_W^2-m_N^2)p_{\ell\perp}xE_pe^{-y_\ell}\right] \end{aligned} \tag{8}$$

$$\begin{aligned} A(\ell^+W^-) &= |(V\xi)_{\ell N}|^2\frac{4\hat{s}m_N^2}{m_W^2} \\ &\quad \left[(m_N^2-m_W^2)(\hat{s}-2m_W^2)+2(2m_W^2-m_N^2)p_{\ell\perp}(xE_pe^{-y_\ell}+E_ee^{y_\ell})\right] \end{aligned} \tag{9}$$

$$\begin{aligned} B(\ell^+W^-) &= |(V\xi)_{\ell N}|^2\frac{4m_N^2(\hat{s}(1-y)-m_N^2)}{m_W^2} \\ &\quad \left[\hat{s}(1-y)(m_N^2-m_W^2)+2(2m_W^2-m_N^2)p_{\ell\perp}xE_pe^{-y_\ell}\right] \end{aligned} \tag{10}$$

and for the neutral decay $N\rightarrow\nu_\ell Z$ by [Ing93]

$$A(\nu_\ell Z) = |\xi_{\nu_\ell N}|^2\frac{2\hat{s}(\hat{s}-m_N^2)(m_N^2-m_Z^2)(m_N^2+2m_Z^2)}{\cos^2\theta_W m_Z^2} \tag{11}$$

$$B(\nu_\ell Z) = |\xi_{\nu_\ell N}|^2\frac{2\hat{s}(1-y)(\hat{s}(1-y)-m_N^2)(m_N^2-m_Z^2)(m_N^2+2m_Z^2)}{\cos^2\theta_W m_Z^2} \tag{12}$$

The total width of the heavy Majorana neutrino is given by

$$\begin{aligned}\Gamma_N &= \sum_{\ell} \frac{G_F}{8\sqrt{2}\pi m_N^3} \left[2|(V\xi)_{\ell N}|^2 (m_N^2 - m_W^2)^2 (m_N^2 + 2m_W^2)\right. \\ &\left. \qquad + |\xi_{\nu_\ell N}|^2 (m_N^2 - m_Z^2)^2 (m_N^2 + 2m_Z^2)\right] \end{aligned} \tag{13}$$

and the partial widths are

$$\Gamma(N \to \ell^\pm W^\mp) = \frac{|(V\xi)_{\ell N}|^2}{8\sqrt{2}\pi} \frac{G_F}{m_N^3} (m_N^2 + 2m_W^2)(m_N^2 - m_W^2)^2 \tag{14}$$

$$\Gamma(N \to \nu_\ell Z) = \frac{|\xi_{\nu_\ell N}|^2}{8\sqrt{2}\pi} \frac{G_F}{m_N^3} (m_N^2 + 2m_Z^2)(m_N^2 - m_Z^2)^2 \tag{15}$$

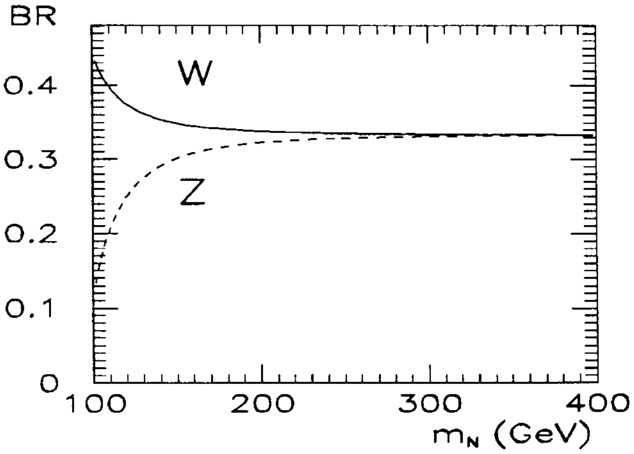

Figure 2: *Branching ratios for* $N \to \ell^\pm W^\mp$ *(full curve) and* $N \to \nu_\ell Z^0$ *(dashed curve) as a function of the Majorana neutrino mass* m_N.

Assuming the Kobayashi-Maskawa type matrix V for the lepton sector to be diagonal, so that $|(V\xi)_{\ell N}| = |\xi_{\nu_\ell N}|$, we obtain the branching ratios shown in Fig. 2. Although all three are 1/3 at large Majorana neutrino masses, for masses not far above the W and Z masses there is a substantial phase space suppression of the decay into the Z.

For a detailed study on present limits on Majorana neutrino masses and mixings, as well as their phenomenology and suitable search strategies at *ep* colliders we refer to [Ing93].

2 The Monte Carlo implementation

The importance sampling method is used to generate phase space points according to the complete differential cross-section formula given by Eq. (2). In short, the importance sampling method can be described as a variable transformation,

$$(x, y, p_{\ell\perp}, y_\ell) \to (H_x(x), H_y(y), H_{p_{\ell\perp}}(p_{\ell\perp}), H_{y_\ell}(y_\ell)) \tag{16}$$

where

$$
\begin{aligned}
H_x(x) &= \int_{x_{\rm min}}^{x} h_x(x')dx' && (17)\\
H_y(y) &= \int_{y_{\rm min}}^{y} h_y(y')dy' && (18)\\
H_{p_{\ell\perp}}(p_{\ell\perp}) &= \int_{p_{\ell\perp{\rm min}}}^{p_{\ell\perp}} h_{p_{\ell\perp}}(p'_{\ell\perp})dp'_{\ell\perp} && (19)\\
H_{y_\ell}(y_\ell) &= \int_{y_{\ell\,{\rm min}}}^{y_\ell} h_{y_\ell}(y'_\ell)dy'_\ell && (20)
\end{aligned}
$$

and h are the so called weighting functions. A phase-space point, $(x, y, p_{\ell\perp}, y_\ell)$ is first chosen from the inverse of the integrals, *e.g.* $x = H_x^{-1}(RH_x(x_{\rm max}))$ where R is a random number, $R \in]0,1[$. The probability for keeping the point is then given by the so called 'g-function',

$$
g(x, y, p_{\ell\perp}, y_\ell) = \frac{d\sigma}{dx\,dy\,dp_{\ell\perp}\,dy_\ell}\,\frac{H_x(x_{\rm max})H_y(y_{\rm max})H_{p_{\ell\perp}}(p_{\ell\perp{\rm max}})H_{y_\ell}(y_{\ell\,{\rm max}})}{h_x(x)h_y(y)h_{p_{\ell\perp}}(p_{\ell\perp})h_{y_\ell}(y_\ell)} \qquad (21)
$$

divided by its maximum. The weighting functions h should be chosen to mimic the characteristic behaviour of the differential cross-section. This makes the function g smooth which is important to make the rejection technique efficient. For details on the Monte Carlo methods used, see [Rat92a].

From the phase space point $(x, y, p_{\ell\perp}, y_\ell)$, the four-momenta of the particles (partons) in the Feynman diagram, Fig. 1, are calculated. The Lund Monte Carlo programs LEPTO 6.1 [Ing92] and JETSET 7.3 [Sjö92] are then used to produce a complete final state of observable particles. The on-shell W/Z (from the heavy neutrino decay) is decayed with the proper branching ratios into a lepton pair or a $q\bar{q}'$ pair, where the polarisation of the W/Z is not taken into account. In the latter decay mode of the W/Z boson, parton showers are included to account for QCD radiation of additional partons, and this parton system is then hadronised using the Lund string model [And83, Sjö92]. Similarly, the quark coming into and leaving the deep inelastic scattering may radiate partons through initial and final state parton showers. Together with the proton remnant spectator, this parton system is hadronised with the Lund model. Thus, the complete 'history' of the event is generated resulting in a complete final state. For a more complete description of the implementation, see [Rat92a].

3 Description of program components

The program is written in FORTRAN 77 and consists of a set of subroutines that must be activated by the users main steering program, which should call the subroutine MAINIT to initialize the generator and then call the subroutine MAJOR for each new event to be generated. All subroutine and common-block names start with MA to indicate origin and avoid name clashes. Exceptions are LSIGMX, which replaces a subroutine in LEPTO 6.1 with the same name, and the real function AMGFUN which starts with AM to follow the FORTRAN name convention.

3.1 Subroutines and functions

The following subroutines should be called by the user:

SUBROUTINE MAINIT

Purpose: Initiate constants and starting values. Calculate the maxima of the g-function, Eq. (21), if not given by the user. **Has to be called once before MAJOR is called.**
Called by: User
Calls to: LINIT, MADEFM, MADMAX

SUBROUTINE MAJOR

Purpose: Administer the generation of one event, calculate the four momenta and fill the event record. **Has to be called once for every event to be generated.**
Called by: User
Calls to: MAGENE, MAFLAV, MAERRM, LSHOWR, LUSHOW, LUPREP, LUEDIT, LUDBRB, LUROBO, LUEXEC
Functions used: ULMASS, RLU, ULANGL, LUCOMP, PLU

The following subroutines and functions are called internally:

SUBROUTINE MADEFM

Purpose: Define the Majorana neutrino in JETSET 7.3 code (KF=79).
Called by: MAINIT
Calls to: -

SUBROUTINE MADMAX

Purpose: Set appropriate starting values for MINUIT [Jam75] and call MINUIT for the calculation of the maxima of the g-function.
Called by: MAINIT
Calls to: LMINEW

SUBROUTINE LSIGMX(NPAR,DERIV,DIFSIG,XF,NFLAG)

Purpose: Is called by MINUIT and is used as an interface to the g-function AMGFUN. Gives minus the g-function if within range and otherwise it gives the square of the distance to the limit. The search for the maximum is done along the singularity of the g-function (only x and y varies freely while $p_{\ell\perp}$ and y_ℓ are calculated from x and y). Stores the maxima found by MINUIT in the array GMAX. For details, see [Rat92a].
Called by: MINUIT-subroutines
Calls to: MAERRM
Remark: Replaces the routine in LEPTO 6.1 with the same name.
Functions used: AMGFUN

SUBROUTINE MAGENE

Purpose:	Generate a phase space point according to the differential cross-section.
Called by:	MAJOR
Calls to:	-
Functions used:	RLU, AMGFUN

REAL FUNCTION AMGFUN(C)

Purpose:	Calculate the value of the g-function, Eq. (21), in a given phase space point.
Called by:	LSIGMX, MAGENE
Calls to:	PYSTFU

SUBROUTINE MAFLAV(NINITQ,NSCATQ)

Purpose:	Choose flavour of initial quark and scattered quark at the boson vertex according to the relative cross-sections and the CKM matrix.
Called by:	MAJOR
Calls to:	-
Functions used:	RLU, LUCOMP

SUBROUTINE MAERRM(CHERRM,ERRVAL)

Purpose:	Handle errors and write error messages.
Called by:	MAJOR, LSIGMX, MAGENE, AMGFUN
Calls to:	-

The following subroutines (S) and functions (F) in LEPTO 6.1 (L) and JETSET 7.3 (J) are used:

Routine		*Purpose*
LINIT	(S/L)	Initialize LEPTO
LSHOWR	(S/L)	Include parton cascades
LMINEW	(S/L)	LEPTO adaption of MINUIT-routine
PYSTFU	(S/L)	Give the parton distribution functions
LUDBRB	(S/J)	Perform rotation and boost in double precision
LUROBO	(S/J)	Perform rotation and boost in single precision
LUSHOW	(S/J)	Generate timelike parton showers
LUPREP	(S/J)	Rearrange parton shower end products
LUEDIT	(S/J)	Exclude unstable or undetectable jets/particles from the event record
LUEXEC	(S/J)	Administrate the fragmentation and decay chain
ULMASS	(F/J)	Give the mass of a parton/particle
RLU	(F/J)	Generate a (pseudo)random number uniformly in $0 < RLU < 1$
ULANGL	(F/J)	Calculate the angle from the x and y coordinates
LUCOMP	(F/J)	Give the compressed parton/particle code
PLU	(F/J)	Provide various real-valued event data

3.2 Common blocks

The common-block mainly intended for communication with the program is MAUSER, which sets switches, parameters and cuts. In addition, all kinematic variables for a given event can be found in MAKINE and LUJETS in JETSET 7.3 is used to store the event record. All variables are given sensible default values in the block data MADATA and all variable names obey the following name convention: integers start with I-N, single precision reals start with A-C,E-H and O-Z and double precision reals start with D.

COMMON /MAUSER/ MAFLAG(20),CUTM(12),PARM(30)

Switches for controlling the program:

MAFLAG(1)	(D=1) choice of parameterisation for the parton densities in the proton. Is transferred to LST(15) in LEPTO [Ing92] which in version 6.1 gives the following choices. (For information on how to use PAKPDF [Cha92] and PDFLIB [Plo93], see LST(16) in LEPTO.)
=1	Eichten-Hinchliffe-Lane-Quigg set 1 [Eic84]
=2	Eichten-Hinchliffe-Lane-Quigg set 2 [Eic84]
=3	Duke-Owens set 1 [Duk84]
=4	Duke-Owens set 2 [Duk84]
=5	Morfin-Tung set 1 [Mor90]
=6	Morfin-Tung set 2 [Mor90]
=7	Morfin-Tung set 3 [Mor90]
=8	Morfin-Tung set 4 [Mor90]
=9	Gluck-Reya-Vogt LO set [Glü90]
=10	Gluck-Reya-Vogt HO set [Glü90]
MAFLAG(2)	(D=0) choice of factorisation scale μ^2 used in the structure-functions
=0	Q^2
=1	$p_{N\perp}^2$, the transverse momentum of the neutrino squared
=2	the constant given in PARM(4)
MAFLAG(3)	(D=0) regulates the final-state lepton status in the event record, K(I,1)
=0	active final-state lepton, K(I,1)=1
=1	inactive final-state lepton, K(I,1)=21
MAFLAG(4)	(D=1) regulates the direction of the x-axis (z-axis in proton direction)
=0	the x-axis along $p_{N\perp}$
=1	event rotated randomly in azimuthal angle between 0 and 2π
MAFLAG(5)	(D=1) regulates the hadronisation
=0	hadronisation off
=1	hadronisation on
MAFLAG(6)	(D=0) regulates the amount of written output.
=0	all output except MINUIT-output
=5	all output
MAFLAG(7)	(D=0) regulates the choice of N-decay channel
=0	mixed according to branching ratios
=1	$e^-p \to NX \to e^+W^-X$
=2	$e^-p \to NX \to e^-W^+X$
=3	$e^-p \to NX \to \nu ZX$
MAFLAG(8)	(D=2) simulation of QCD effects in the scattered quark and proton remnant system (for 2-5 *cf.* LST(8) in LEPTO [Ing92])
=1	final state radiation from the scattered quark only, using a simplified treatment (LUSHOW is used on the quark and diquark system).

Only valence quarks, *i.e.* u-quarks, are considered in the proton.
=2 initial and final state radiation
=3 initial state radiation
=4 final state radiation
=5 QCD switched off but target remnant as 2, 3 and 4

MAFLAG(9) error flag
=1 maximum of g-function violated. This is **serious** if the violation is large and in that case the user has to either set the maxima by hand (see MAFLAG(19)) or change the h-functions to make the g-function smoother
=LST(21) error information transferred from LEPTO

MAFLAG(10) (D=1) Error handling
=0 execution not stopped on error
=1 warnings printed but execution not stopped
=2 warnings printed and execution stopped

MAFLAG(11) (D=2) choice of h_x-function (see Section 2 for definition and steering program example in Section 4 for suitable choices)
=-2 $h_x(x) = 1/x^2$
=-1 $h_x(x) = 1/x$
=0 $h_x(x) = const.$
=1 $h_x(x) = \exp(-A_x x)$
=2 $h_x(x) = x\exp(-A_x x^2)$

MAFLAG(12) (D=0) regulates calculation of A_x
=0 A_x is calculated by the program
=1 A_x is given in PARM(8)

MAFLAG(13) (D=1) choice of h_y-function (see Section 2 for definition and steering program example in Section 4 for suitable choices)
=-2 $h_y(y) = 1/y^2$
=-1 $h_y(y) = 1/y$
=0 $h_y(y) = const.$
=1 $h_y(y) = \exp(-A_y y)$
=2 $h_y(y) = y\exp(-A_y y^2)$

MAFLAG(14) (D=0) regulates calculation of A_y
=0 A_y is calculated by the program
=1 A_y is given in PARM(9)

MAFLAG(15) (D=2) choice of $h_{p_{\ell\perp}}$-function (see Section 2 for definition and steering program example in Section 4 for suitable choices)
=-2 $h_{p_{\ell\perp}}(p_{\ell\perp}) = 1/{p_{\ell\perp}}^2$
=-1 $h_{p_{\ell\perp}}(p_{\ell\perp}) = 1/p_{\ell\perp}$
=0 $h_{p_{\ell\perp}}(p_{\ell\perp}) = const.$
=1 $h_{p_{\ell\perp}}(p_{\ell\perp}) = \exp(-A_{p_{\ell\perp}} p_{\ell\perp})$
=2 gives $h_{p_{\ell\perp}}(p_{\ell\perp}) = p_{\ell\perp}\exp(-A_{p_{\ell\perp}} {p_{\ell\perp}}^2)$

MAFLAG(16) (D=0) regulates calculation of $A_{p_{\ell\perp}}$ for $N \to e^{\pm}W^{\mp}$
=0 $A_{p_{\ell\perp}}$ is calculated by the program
=1 $A_{p_{\ell\perp}}$ is given in PARM(10)

MAFLAG(17) (D=0) regulates calculation of $A_{p_{\ell\perp}}$ for $N \to \nu Z$
=0 $A_{p_{\ell\perp}}$ is calculated by the program
=1 $A_{p_{\ell\perp}}$ is given in PARM(11)

MAFLAG(18) (D=1) choice between fixed and varying (according to a Breit-Wigner distribution) boson-masses in the neutrino decay
  =0 fixed boson-masses
  =1 varying boson-masses
MAFLAG(19) (D=0) regulates calculation of g-function (see section 2) maxima
  =0 maxima of g-functions are calculated
  =1 maxima of g-functions given in PARM(12) to PARM(17)
MAFLAG(20) not used

Cuts on kinematic variables defined in Section 1:
CUTM(1): $x_{\min}$ (default=0.)
CUTM(2): $x_{\max}$ (default=1.)
CUTM(3): $y_{\min}$ (default=0.)
CUTM(4): $y_{\max}$ (default=1.)
CUTM(5): $Q^2_{\min}$ (default=4. GeV^2)
CUTM(6): $Q^2_{\max}$ (default=10^8 GeV^2)
CUTM(7): $W^2_{\min}$ (default=9. GeV^2)
CUTM(8): $W^2_{\max}$ (default=10^8 GeV^2)
CUTM(9): $p_{\ell\perp\min}$ (default=0. GeV)
CUTM(10): $p_{\ell\perp\max}$ (default=1000 GeV)
CUTM(11): $y_{\ell\min}$ (default=−100)
CUTM(12): $y_{\ell\max}$ (default=100)

Parameters for input (1-20) and output (21-30):
PARM(1): Mass of heavy Majorana neutrino in GeV (default=100 GeV)
PARM(2): Proton-momentum in GeV (default=820 GeV)
PARM(3): Electron-momentum in GeV (default=30 GeV)
PARM(4): Value of fixed factorisation scale μ^2 in GeV^2 used when evaluating the structure functions (if MAFLAG(2)=2) (default=1000 GeV^2)
PARM(5): Degree of mixing between light and heavy Majorana neutrinos, $|(V\xi)_{eN}|^2 = |\xi_{\nu_e N}|^2$ (default=0.01)
PARM(6): Cut used around the singularity of the g-function (see ALSCUT in [Rat92a] for details). A larger cut will speed up the simulation but at the same time increase the risk of violating the maximum of the g-function and cut away a larger part of the phase-space. (default=0.001)
PARM(7): Safety factor, multiplies the maxima of the g-function. (default=1.1)
PARM(8): A_x (see also MAFLAG(12))
PARM(9): A_y (see also MAFLAG(14))
PARM(10): $A_{p_{\ell\perp}}$ for $N \to e^{\pm}W^{\mp}$ (see also MAFLAG(16))
PARM(11): $A_{p_{\ell\perp}}$ for $N \to \nu Z$ (see also MAFLAG(17))
PARM(12): Max of first part of g-function for $N \to e^+W^-$ (see also MAFLAG(19))
PARM(13): Max of second part of g-function for $N \to e^+W^-$ (see also MAFLAG(19))
PARM(14): Max of first part of g-function for $N \to e^-W^+$ (see also MAFLAG(19))
PARM(15): Max of second part of g-function for $N \to e^-W^+$ (see also MAFLAG(19))
PARM(16): Max of first part of g-function for $N \to \nu Z$ (see also MAFLAG(19))
PARM(17): Max of second part of g-function for $N \to \nu Z$ (see also MAFLAG(19))
PARM(18): not used

PARM(19): not used
PARM(20): not used
PARM(21): Estimation[1] of the cross-section in *pb* for $e^-p \to NX \to e^+W^-X$ with the cuts taken into account.
PARM(22): Estimation[1] of the standard deviation in PARM(21)
PARM(23): Estimation[1] of the cross-section in *pb* for $e^-p \to NX \to e^-W^+X$ with the cuts taken into account.
PARM(24): Estimation[1] of the standard deviation in PARM(23)
PARM(25): Estimation[1] of the cross-section in *pb* for $e^-p \to NX \to \nu ZX$ with the cuts taken into account.
PARM(26): Estimation[1] of the standard deviation in PARM(25)
PARM(27): Efficiency[2] in the generation for $e^-p \to NX \to e^+W^-X$
PARM(28): Efficiency[2] in the generation for $e^-p \to NX \to e^-W^+X$
PARM(29): Efficiency[2] in the generation for $e^-p \to NX \to \nu ZX$
PARM(30): not used

COMMON /MAKINE/ EP,EE,S,SHAT,Q2,W2,X,Y,PNT,PNL,YN,EN, PLT,YL

EP: Proton energy in GeV
EE: Electron energy in GeV
S: CMS-energy squared (Mandelstam s) in GeV^2
SHAT: $\hat{s} = x\,s$
Q2: Momentum transfer squared, $Q^2 = -q^2$ in GeV^2
W2: Hadronic CMS-energy squared, $W^2 = (p_p + q)^2$ in GeV^2
X: Bjorken-x, $x = Q^2/2p_p \cdot q$
Y: Standard y-variable, $y = p_p \cdot q/p_p \cdot p_e$
PNT: Transverse momentum of heavy $p_{N\perp}$ Majorana neutrino in GeV
PNL: Longitudinal momentum of heavy Majorana neutrino in GeV
YN: Rapidity y_N of heavy Majorana neutrino
EN: Energy of heavy Majorana neutrino in GeV
PLT: Transverse momentum $p_{\ell\perp}$ of final-state lepton in GeV
YL: Rapidity y_ℓ of final-state lepton

COMMON /LUJETS/ N,K(4000,5),P(4000,5),V(4000,5)

The variables in the common-block LUJETS are described in the JETSET 7.3 manual [Sjö92]. The first seven entries in the event record are as follows (in the lab frame with the z-axis in the proton direction):

1. Incoming electron
2. Incoming proton
3. Exchanged W-boson
4. Heavy Majorana neutrino
5. Incoming parton before initial shower
6. Incoming quark at boson vertex
7. Scattered quark at boson vertex before final shower

The decay products from the N-decay are in line K(4,4) (final state lepton) and

---

[1] The estimation is updated for each event so it should not be used until all events have been generated.

[2] The efficiency is given by the number of accepted events divided by the number of tries.

K(4,5) (on shell boson) respectively.

The following common-blocks are mainly for internal use.

COMMON /MACROS/ DTRIES(3),DFCNSM(3),TCROSS(3),PCROSS(-6:6),
NCALLS

DTRIES(3):	Number of phase space points tried for respective N decay channel
DFCNSM(3):	Sum of g-function values in all tried points for respective channel
TCROSS(3):	Monte Carlo estimation of the total cross-section in pb for the channel in question (without cuts).
PCROSS(IFL):	The relative cross-section for incoming quark of flavour IFL, IFL=-6,..,-1,1,..,6 in a given event
PCROSS(0):	Sum of the relative cross-sections in a given event
NCALLS:	Number of calls to MAJOR

COMMON /MAMAMI/ XMAX,XMIN,YMAX,YMIN,PLTMAX,PLTMIN

XMAX, XMIN:	Phase space limits for x, Eq. (3) in current event
YMAX, YMIN:	Phase space limits for y, Eq. (4) in current event
PLTMAX, PLTMIN:	Phase space limits for $p_{\ell\perp}$, Eq. (5)

COMMON /MAMASS/ AMB,AMB2,AMW,AMW2,AMN,AMN2,AMNT,
AMZ,AMZ2

AMB (AMB2):	Mass of boson (squared) from Majorana neutrino decay in current event (fixed or according to Breit-Wigner distribution), in GeV (GeV^2)
AMW (AMW2):	Mass of W-boson (squared), m_W (fixed), in GeV (GeV^2)
AMN (AMN2):	Mass of heavy Majorana neutrino (squared), m_N in GeV (GeV^2)
AMNT:	Transverse mass of heavy Majorana neutrino, $m_{N\perp} = \sqrt{m_N^2 + p_{N\perp}^2}$, in GeV
AMZ (AMZ2):	Mass of Z-boson (squared), m_Z (fixed), in GeV (GeV^2)

COMMON /MACONS/ PI,FCONST,BR1,BR2,BR3

PI:	π=3.1415927
FCONST:	Constant factor in the differential cross-section
BR1:	Branching ratio for the decay $N \to e^+W^-$
BR2:	Branching ratio for the decay $N \to e^-W^+$
BR3:	Branching ratio for the decay $N \to \nu Z$

COMMON /MAGSPE/ GMAX(3,2),ALS,ARS,ALSCUT,AX,AY,APLT,
NGIND,NPROC

GMAX(1,1):	Max of first part of g-function for $N \to e^+W^-$
GMAX(1,2):	Max of second part of g-function for $N \to e^+W^-$
GMAX(2,1):	Max of first part of g-function for $N \to e^-W^+$
GMAX(2,2):	Max of second part of g-function for $N \to e^-W^+$
GMAX(3,1):	Max of first part of g-function for $N \to \nu Z$
GMAX(4,2):	Max of second part of g-function for $N \to \nu Z$
ALS:	Lower phase space limit of $\omega = \cosh(y_N - y_\ell)$, Eq. (6), in current event
ARS:	Upper phase space limit of $\omega = \cosh(y_N - y_\ell)$, Eq. (6), in current event
ALSCUT:	Cut around the singularity ALS $= \omega = 1$

AX:	Constant in h_x-function
AY:	Constant in h_y-function
APLT:	Constant in $h_{p_{\ell\perp}}$-function
NGIND:	Second argument to the GMAX-matrix
NPROC:	First argument to the GMAX-matrix

The following common-blocks in LEPTO 6.1 are used:

```
COMMON /LEPTOU/ CUT(14),LST(40),PARL(30),GX,GY,GW2,GQ2,GU
COMMON /LBOOST/ DBETA(2,3),STHETA(2),SPHI(2),PB(5),PHIR
COMMON /LFLMIX/ CABIBO(4,4)
COMMON /LPFLAG/ LST3
COMMON /LMINUI/ XKIN,UKIN,WKIN,AIN,BIN,MAXFIN,RELUP,RELERR,
          RELER2,FCNMAX
COMMON /LMINUC/ NAMKIN(4),NAM(30)
COMMON /PYPARA/ IPY(80),PYPAR(80),PYVAR(80)
```

The following common-blocks in JETSET 7.3 are used:

```
COMMON /LUDAT1/ MSTU(200),PARU(200),MSTJ(200),PARJ(200)
COMMON /LUDAT2/ KCHG(500,3),PMAS(500,4),PARF(2000),VCKM(4,4)
COMMON /LUDAT3/ MDCY(500,3),MDME(2000,2),BRAT(2000),KFDP(2000,5)
COMMON /LUDAT4/ CHAF(500)
```

3.3 Update history

Updates from version 1.1 [Rat92b] to 1.3:

- inclusion of the neutral current decay $N \rightarrow \nu_\ell Z$
- extension and redefinition of the common-block MAUSER and some internal common-blocks
- inclusion of a subroutine for error handling
- correction of a small error in the differential cross-section

4 Usage and availability

MAJOR 1.3 should be loaded together with LEPTO 6.1 [Ing92] and JETSET 7.3 [Sjö92]. To run the generator you need a steering program which could look something like the following

```
      PROGRAM MAJDEMO

      COMMON /MAUSER/ MAFLAG(20),CUTM(12),PARM(30)

C--       set mixing
      PARM(5)=0.01
C--       set heavy Majorana neutrino mass
      PARM(1)=100.
C--       set proton and electron momentum
      PARM(2)=820.
      PARM(3)=30.
C--       choose appropriate h-functions
C--       at HERA (30+820), mN=100
      MAFLAG(11)=2
      MAFLAG(13)=1
      MAFLAG(15)=2
C--       at LEP/LHC (50+8000), mN=100, 300
C       MAFLAG(11)=-1
C       MAFLAG(13)=-1
C       MAFLAG(15)=2
C--       at LEP/LHC (50+8000), mN=500, 700
C       MAFLAG(11)=-2
C       MAFLAG(13)=-1
C       MAFLAG(15)=2

C--       initialise
      CALL MAINIT

C--       generate 1000 events according to the cross-section
      DO 100 J=1,1000
      CALL MAJOR
100   CONTINUE

      WRITE(*,*) 'The total cross-section for e- P --> e+ W- X =',
     ,            PARM(21),' [pb]'
      WRITE(*,*) 'With an estimated standard deviation of:',
     ,            PARM(22),' [pb]'
      WRITE(*,*) 'The total cross-section for e- P --> e- W+ X =',
     ,            PARM(23),' [pb]'
      WRITE(*,*) 'With an estimated standard deviation of:',
     ,            PARM(24),' [pb]'
      WRITE(*,*) 'The total cross-section for e- P --> nu Z X =',
     ,            PARM(25),' [pb]'
      WRITE(*,*) 'With an estimated standard deviation of:',
     ,            PARM(26),' [pb]'

      END
```

Information about the program, the source code and a demonstration job can be found on the DESY IBM, VAX and hp systems:

DSYIBM	VXDESY	hp	! system
	DISK$T__:	/usr/users/rathsman	! directory
T00ING.LUND	[INGELMAN.LUND]	/lund/major/major13	
(MAJORINF)	MAJOR.INFO	README	! information
(MAJOR13)	MAJOR13.FOR	major13.f	! source code
(MAJDEMO)	MAJDEMO.FOR	majdemo.f	! demo job
(MAJORTEX)	MAJOR13.TEX	major13.tex	! manual in LaTeX
	MAJOR13.COM	Makefile	! makefile

For UNIX users there is a packed version, major13.tar.gz, on the hp system which can be found in /usr/users/rathsman/lund/major. To install the program on the DESY hp one then does something like the following:

```
> zcat major13.tar.gz | tar -xf -
> cd major13
major13> make
```

On other UNIX systems one has to check that the macros in the Makefile are valid.

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