29th International Cosmic Ray Conference Pune (2005) **9**, 93–96

All Lepton Propagation Monte Carlo

D. Chirkin[a] and W. Rhode[b]

(a) Lawrence Berkeley National Lab Berkeley, CA 94720-8158, U.S.A.

(b) University of Dortmund, D-44221 Dortmund, Germany

Presenter: D. Chirkin (dchirkin@lbl.gov), usa-chirkin-D-abs2-he21-poster

The muon propagation Monte Carlo (MMC) is a software program originally only used for muon and tau charged lepton propagation through various media or their combinations. Introduced in 2001, it is capable of propagating leptons of energies from their rest mass to $10^{20} - 10^{30}$ eV (extrapolating known cross sections to high energies). It now takes into account a multitude of effects (LPM and dielectric suppressions, decay, Moliere scattering) and implements several bremsstrahlung and photonuclear cross section parameterizations. The program has been extended to also calculate neutrino cross sections (using native CTEQ routines) and to propagate all of the neutrinos and charged leptons. All lepton particles created during the propagation are also propagated until they exit the detector or disappear. Neutrino oscillations at low energies ($\nu_\mu \leftrightarrow \nu_\tau$) are considered, and $\tau \leftrightarrow \nu_\tau$ oscillations are simulated. Additionally, the program now includes a phenomenological atmospheric neutrino generator, which relies on fits to CORSIKA-simulated flux of atmospheric leptons. It also implements curved atmosphere (and Earth surface for detectors at depth) treatments, and accounts for muon energy losses and decay. Although the core of the program is written in Java, its distribution now includes a c/c++ interface package. The same java executable is used in AMANDA and IceCube simulation chains, and at the MMC homepage at a demonstration applet.

1. Introduction

MMC was first introduced at [1]. Since then it has been extensively used in data simulations of several experiments with energies spanning from a few GeV to 10^{25} eV. We have implemented a number of new cross section parameterizations, especially useful in the most uncertain case of the photonuclear cross section. All lepton particles (including neutrinos) can now be propagated, and transitions between them are simulated.

2. Precision of MMC

An extensive study of the precision of MMC is presented in our report [2]. The relative uncertainty in reported energy of a propagated muon is shown to be below 0.1 %. Here we demonstrate a wide range of energies over which precise muon propagation with MMC is possible through the following setup. For each muon with the fixed initial energy all secondaries created within the first 800 meters of ice are recorded. The resulting energy transferred to secondaries is shown in fig. 1. Results of running two variants of mudedx (loh and lip) [3], and MUM [4] are also shown. The total energy deposited in the volume of the detector is commensurable between all four propagators in their respective regions of applicability.

Fig. 1 demonstrates the span of energies over which MMC can be used with fixed $E_{cut} = 0.5$ GeV. With such E_{cut}, MMC works for energies up to $0.5 \cdot 10^{15}$ GeV, which is mainly determined by the computer precision with which double precision numbers can be added: $0.5/0.5 \cdot 10^{15} \sim 10^{-15}$. When relative position increments fall below that, the muon "gets stuck" in one point until its energy becomes sufficiently low or it propagates without stochastic losses sufficiently far, so that it can advance again. A muon "stuck" in this fashion still looses the energy, which is why it appears that its losses go up. With fixed $v_{cut} = 10^{-2} - 10^{-3}$ (and apparently as low as $10^{-12} - 10^{-15}$), MMC shows no signs of such deterioration.

3. Parameterizations of the cross sections

Four bremsstrahlung parameterizations implemented in MMC are compared (for muon) in fig. 2. Andreev Berzrukov Bugaev parameterization [5] agrees best with the Kelner Kokoulin Petrukhin parameterization [6] for muons, and with the complete screening case of electrons (shown in [2]), thereby providing the most comprehensive description of the bremsstrahlung cross section.

Bezrukov Bugaev parameterization of the photonuclear cross section [7] is implemented with both the original photon-nucleon parameterization of 1981, and with the Kokoulin [8] and ZEUS [9] parameterizations. Additionally, ALLM [10] and Butkevich-Mikhailov [11] (valid only up to 10^6 GeV) parameterizations were implemented (fig. 3). They do not rely on "nearly-real" exchange photon assumption and involve integration over the square of the photon 4-momentum (Q^2). Also, treatment of the hard component within the Bezrukov-Bugaev parameterization (as calculated in [12]) can optionally be enabled. The nuclear structure function can be evaluated according to formulae summarized in either [11] or [13].

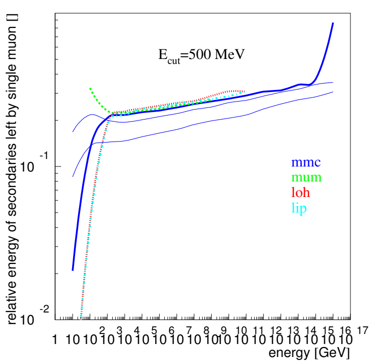

Figure 1. Relative energy of secondaries. Lower mmc curves are for fixed $v_{cut} = 10^{-2}$ and 10^{-3}.

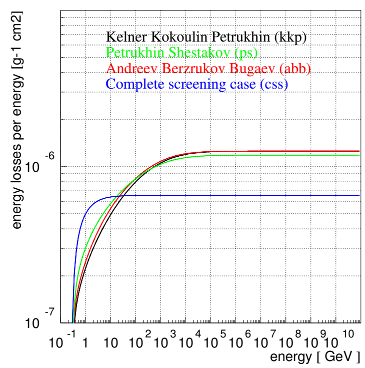

Figure 2. Bremsstrahlung cross section parameterizations for muons

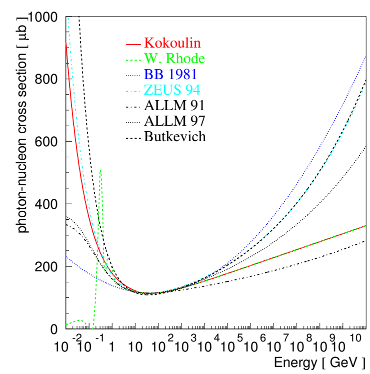

Figure 3. Photon-nucleon cross sections. Curves 5-7 are calculated according to $\sigma_{\gamma N} = \lim_{Q^2 \to 0} \frac{4\pi^2 \alpha F_2^N}{Q^2}$

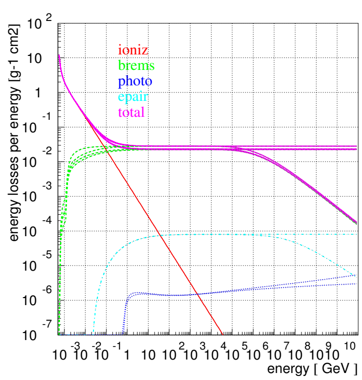

Figure 4. Electron energy losses

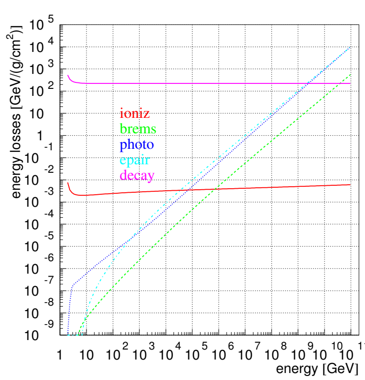

Figure 5. Tau energy losses

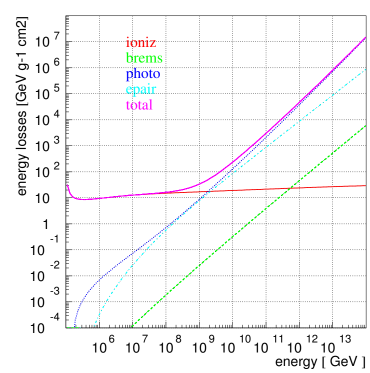

Figure 6. Energy losses of a monopole with mass 100 TeV

4. Electron, tau, and monopole propagation

Electrons, taus, and monopoles can also be propagated with MMC. Bremsstrahlung is the dominant cross section in case of electron propagation, and the complete screening case cross section should be selected. Electron energy losses in Ice are shown in Fig. 4 (also showing the LPM suppression of cross sections).

For tau propagation Bezrukov-Bugaev parameterization with the hard component or the ALLM parametrization should be selected for photonuclear cross section. Tau propagation is quite different from muon propagation because the tau lifetime is 7 orders of magnitude shorter than the muon lifetime. While muon decay can be neglected in most cases of muon propagation, it is the main process to be accounted for in the tau propagation. Fig. 5 compares tau energy losses with losses caused by tau decay (given by $E_\tau/(\rho v_\tau \tau) = m_\tau/(\rho v_\tau \tau_0)$; this is the energy per mwe deposited by decaying taus in a beam propagating though medium with density ρ). In [2] we compare the average range of taus propagated with $v_{cut} = 1$ (completely continuously) and $v_{cut} = 10^{-3}$ (detailed stochastic treatment). Both treatments produce almost identical results. Therefore, tau propagation can be treated continuously for all energies unless one needs to obtain spectra of the secondaries created along the tau track.

For monopole propagation all cross sections except bremsstrahlung (which scales as z^4) are scaled up with a factor z^2, where $z = 1/(2\alpha)$ is the monopole charge (fig. 6).

5. Phenomenological lepton generation and neutrino propagation

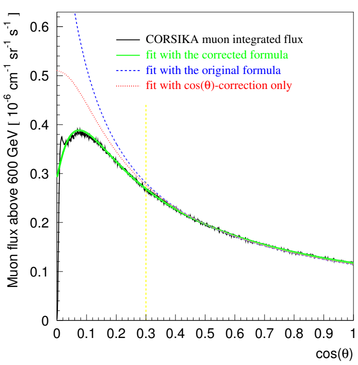

Figure 7. Integrated muon flux at 600 GeV.

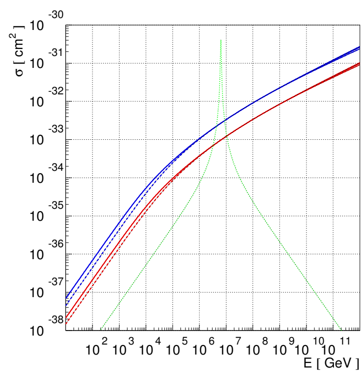

Figure 8. Simulated neutrino cross sections: higher blue curves are CC, lower red curves are NC; solid are ν, dashed are $\bar{\nu}$; green dotted is $\bar{\nu}_e e^- \to W^-$

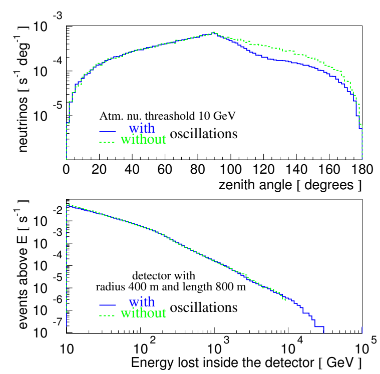

Figure 9. Neutrino flavor oscillations: muon events. Since latitude-dependent geomagnetic cutoff is not calculated, a fixed 10 GeV cutoff is applied (cf. [14]).

MMC allows one to generate fluxes of atmospheric leptons according to parameterizations given in [15]. Earth surface (important for detectors at depth) [16] and atmospheric curvature [17] are accounted for, and so are muon energy losses and probability of decay. Although the reference [15] provides flux parameterization, which is accurate in the region of energies from 600 GeV to 60 TeV, it is possible to introduce a correction to spectral index and normalization of each leptonic component and extrapolate the results to the desired energy range. One can also add an ad-hoc prompt component, specify $E^{-\gamma}$-like fluxes of neutrinos of all flavors, or inject leptons with specified location and momenta into the simulation.

Neutrino cross sections are evaluated according to [18] with CTEQ6 parton distribution functions [19] (fig. 8). Neutrino and anti-neutrino neutral and charged current interaction, as well as Glashow resonance $\bar{\nu}_e e^-$ cross sections are taken into account. Power-law extrapolation of the CTEQ PDFs to small x is implemented to extend the cross section applicability range to high energies. Earth density is calculated according to [20], with a possibility of adding layers of different media. All secondary leptons are propagated, therefore it is possible to simulate particle oscillations, e.g., $\tau \leftrightarrow \nu_\tau$. Additionally, atmospheric neutrino $\nu_\tau \leftrightarrow \nu_\mu$ oscillations are simulated (fig. 9).

6. MMC implementation into detector simulations

MMC was used in the data simulation of the AMANDA, IceCube, and Fréjus experiments. We also know of MMC implementations in data simulations of ANITA and SalSA experiments.

It is possible to use multiple concentric media in MMC, which is important for the study of the muons which might be created in either medium in or around the detector and then propagated toward it. Definition of spherical, cylindrical, and cuboid detector and media geometries is possible. This can be easily extended to describe other shapes.

Having been written in Java, MMC comes with the c/c++ interface package, which simplifies its integration into the simulation programs written in native computer languages. The distribution of MMC also includes a demonstration applet, which allows one to immediately visualize simulated events.

7. Conclusions

New features of the MMC, originally introduced at [1] are presented. The code (available at [2]) has provided an adequate description of data in simulations and studies of systematic uncertainties of several experiments.

References

[1] D. Chirkin & W. Rhode, 27th ICRC, Hamburg, 2001
[2] D. Chirkin & W.Rhode, arXiv:hep-ph/0407075, http://dima.lbl.gov/˜dima/work/MUONPR/
[3] W. Lohmann, R. Kopp, & R. Voss, CERN 85-03, Experimental Physics Division, 21 March 1985
[4] E. Bugaev, I. Sokalski, & S. Klimushin, Phys. Rev. D 64, 074015 (2001)
[5] Yu.M. Andreyev, L.B. Bezrukov, & E.V. Bugaev, Phys. At. Nucl. 57, 2066 (1994)
[6] S.R. Kelner, et al., Preprint of Moscow Engineering Physics Inst., Moscow, 1995, no 024-95
[7] L.B. Bezrukov & E.V. Bugaev, Sov. J. Nucl. Phys. 33(5), May 1981
[8] R.P. Kokoulin, Nucl. Phys. B (Proc. Suppl.) 70 (1999) 475-479
[9] ZEUS Collaboration, Z. Phys. C, 63 (1994) 391
[10] H. Abramowicz, & A. Levy, hep-ph/9712415, 1997
[11] A.V. Butkevich & S.P. Mikheyev, JETP, Vol 95, No 1 (2002) 11, hep-ph/0109060
[12] E. Bugaev, et al., hep-ph/0312295
[13] S. Dutta, et al., Phys. Rev. D 63 (2001) 094020, hep-ph/0012350, 2000
[14] M. Kowalski & A. Gazizov, 28th ICRC, Tsukuba, 2003
[15] D. Chirkin, Fluxes of atmospheric leptons at 600 GeV - 60 TeV, hep-ph/0407078
[16] D.A. Chirkin, Ph.D. thesis, UC Berkeley, 2003
[17] L.V. Volkova, Lebedev Physical Institute Report No. 72, 1969
[18] R. Gandhi, et al., Phys. Rev. D 58, 093009, 1998
[19] J. Pumplin, et al., hep-ph/0201195, http://www.phys.psu.edu/˜cteq/
[20] A. Dziewonski, The Encyclopedia of Solid Earth Geophysics, Van Nostrand Reinhold, New York, 1989