All Lepton Propagation Monte Carlo

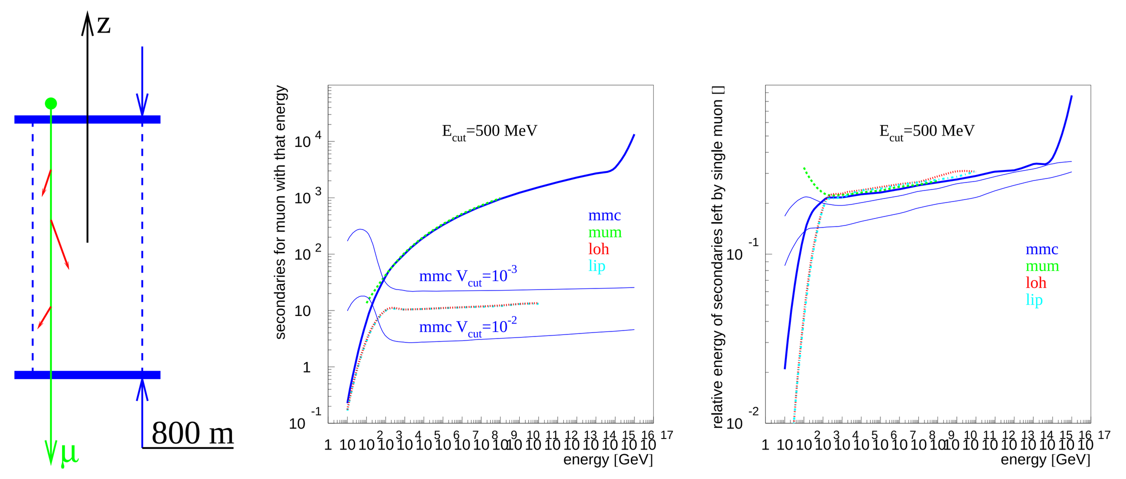
Dmitry Chirkin[1,2], Wolfgang Rhode[2]
[1]Lawrence Berkeley National Laboratory, USA
[2]University of Dortmund, Germany

Introduction

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 [1], 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.

Precision of MMC

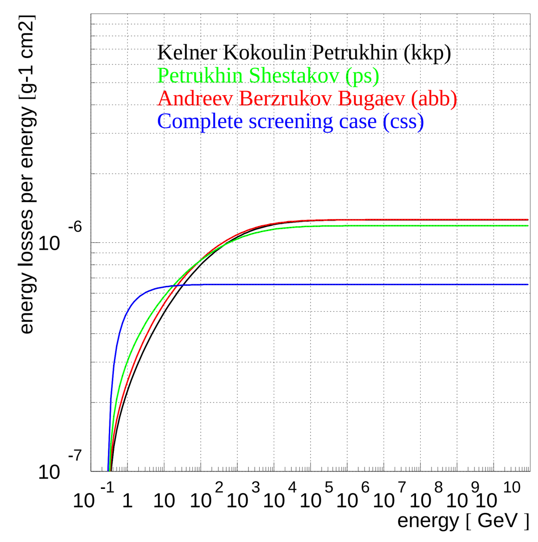
An extensive study of the precision of MMC is presented in our report [2]. The relative uncertainty in reported energy of a propagated muon is shown to be below 0.1 %. Here we demonstrate a wide range of energies over which precise muon propagation with MMC is possible through the following setup. For 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 the figure below.



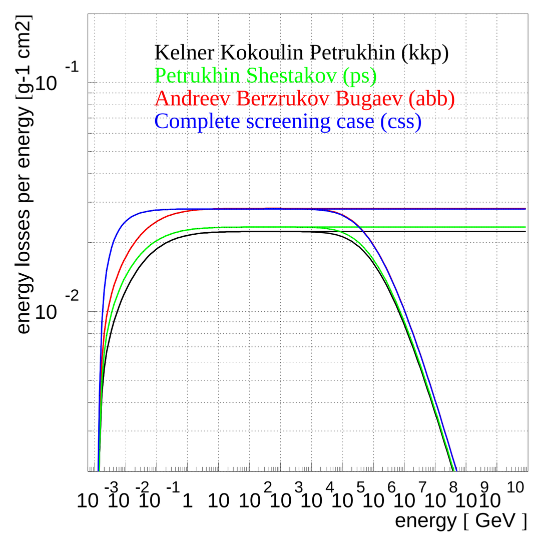
This demonstrates the span of energies over which MMC can be used with fixed $E_{cut} = 0.5$ GeV. With such E_{cut}, MMC works for energies up to $0.5 \cdot 10^{15}$ GeV, which is mainly determined by the computer precision with which double precision numbers can be added: $0.5/0.5 \cdot 10^{15} \sim 10^{-15}$. 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.

Parameterizations of the cross sections

Four bremsstrahlung parameterizations implemented in MMC are compared in the figure below. Andreev Berzrukov Bugaev parameterization agrees best with the Kelner Kokoulin Petrukhin parameterization for muons, and with the complete screening case of electrons, thereby providing the most comprehensive description of the bremsstrahlung cross section.

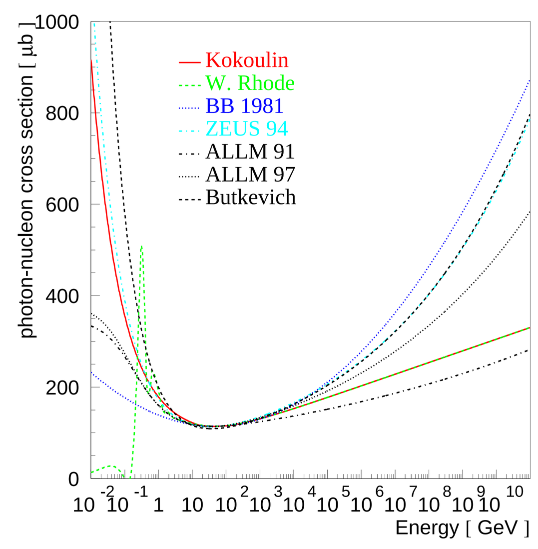


Bremsstrahlung cross section parameterizations for muons

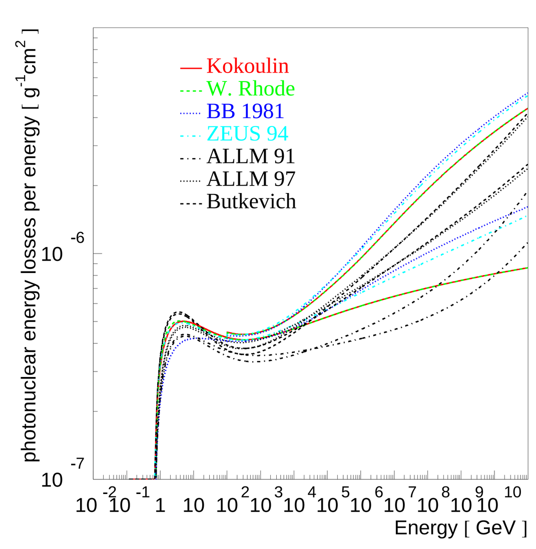


Bremsstrahlung cross section parameterizations for electrons

Bezrukov Bugaev parameterization of the photonuclear cross section is implemented with both the original photon-nucleon parameterization of 1981, and with the Kokoulin and ZEUS parameterizations. Additionally, ALLM and Butkevich-Mikhailov (valid only up to 10^6 GeV) parameterizations were implemented. 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 can optionally be enabled.



Photon-nucleon cross sections: Kokoulin, W. Rhode, Bezrukov-Bugaev 1981, ZEUS 94, ALLM 91 and 97, Butkevich. Curves 5-7 are calculated according to $\sigma_{\gamma N} = \lim_{Q^2 \to 0} \frac{4\pi^2 \alpha F_2^N}{Q^2}$



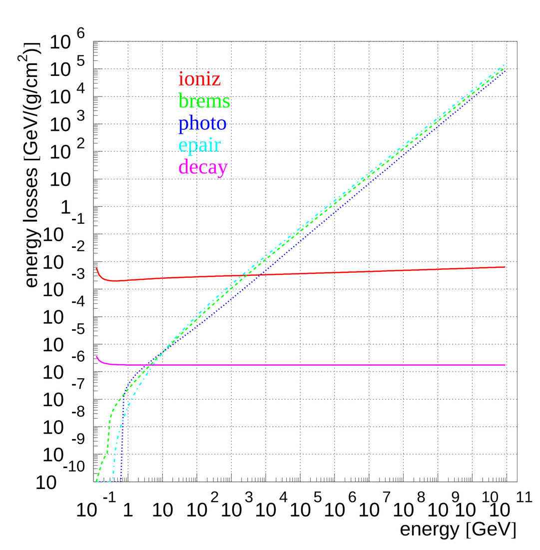
Photonuclear energy losses (divided by energy). Higher lines for the parameterizations 1-4 include the hard component, two sets of lines for 5-7 calculate use different formulae for calculation of shadowing effects

Electron, tau, and monopole propagation

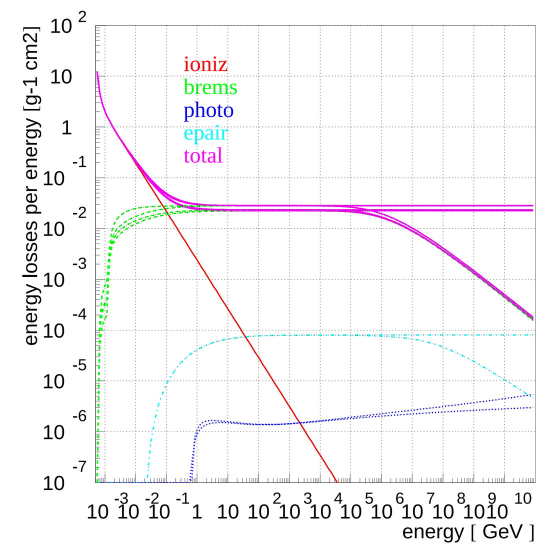
Electrons, taus, and monopoles can also be propagated with MMC. Bremsstrahlung is the dominant cross section in case of electron propagation, and the complete screening case cross section should be selected. Electron energy losses in Ice are shown in the figure below (also showing the LPM suppression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

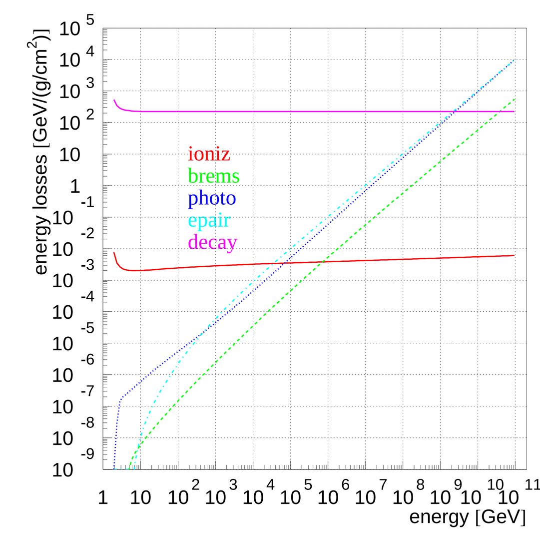
For monopole propagation all cross sections except bremsstrahlung (which scales as z^4) are scaled up with a factor z^2, where $z = 1/(2\alpha)$ is the monopole charge.



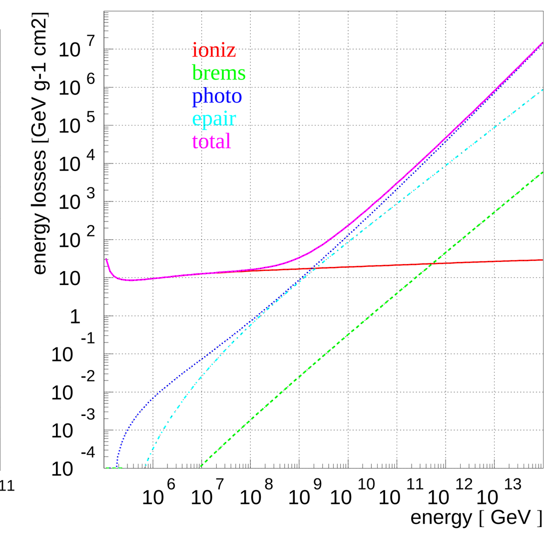
Muon energy losses



Electron energy losses in Ice

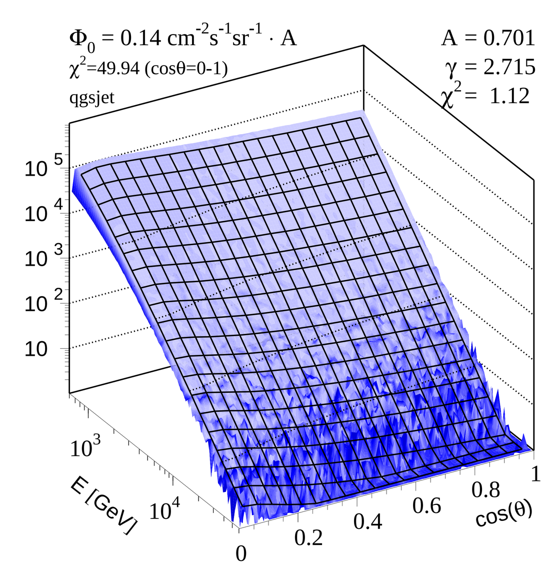


Tau energy losses

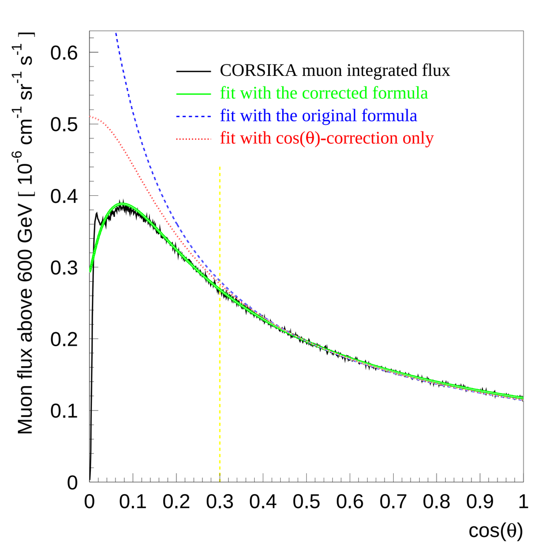


Energy losses of a monopole with mass 100 TeV

Phenomenological lepton generation



Fit with the corrected Gaisser formula.

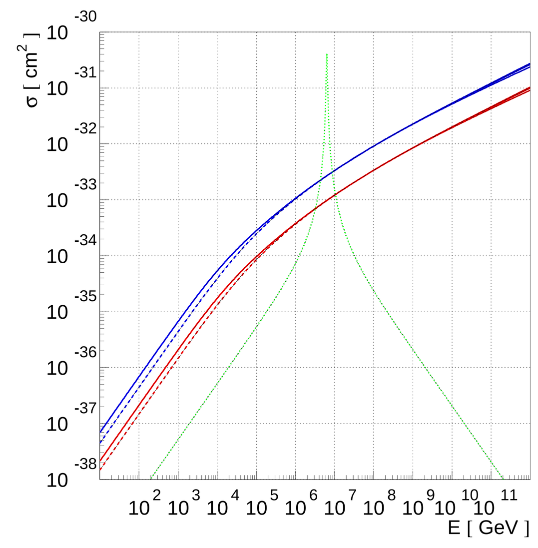


Integrated muon flux at 600 GeV.

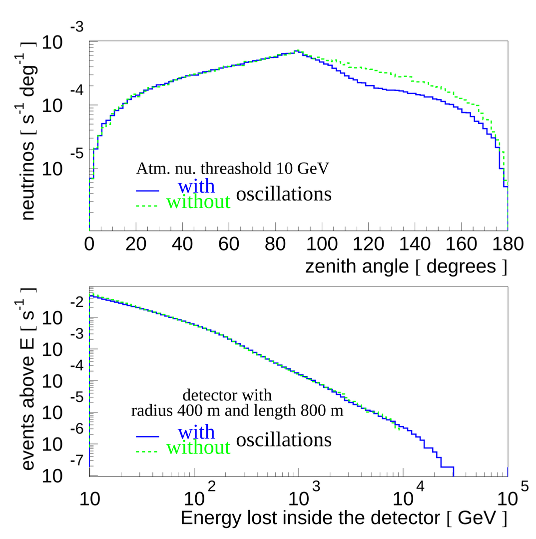
MMC allows one to generate fluxes of atmospheric leptons according to parameterizations given in [3]. Earth surface (important for detectors at depth) and atmospheric curvature are accounted for, and so are muon energy losses and probability of decay. Although [3] provides flux parameterization, which 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 propagation

Neutrino cross sections are evaluated with CTEQ6 parton distribution functions. 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 the preliminary Earth model, 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.



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



Neutrino flavor oscillations: muon events. Since latitude-dependent geomagnetic cutoff is not calculated, a fixed 10 GeV cutoff is applied.

MMC implementations

MMC was used in the data simulations of the AMANDA, IceCube, Fréjus, and several other experiments.

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.

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] D. Chirkin, Fluxes of atmospheric leptons at 600 GeV - 60 TeV, hep-ph/0407078