All Lepton Propagation Monte Carlo

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Introduction

The muon propagation Monte Carlo (MMC) is a software program originally only used for muon and tau charged lepton propagation through various media and combinations. Introduced in 2001 [1], it is capable of propagating leptons of energies from their rest mass to $10^{12}$ - $10^{19}$ eV (extrapolating known cross sections to high energies). It now takes into account a multitude of effects (LPM and dielectric suppressions, decay, Molière scattering) and implement 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 leptons 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 $\nu_\mu \leftrightarrow \nu_e$ 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 curvilinear 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++ 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 range of energies over which MMC can be used with fixed incident energies of up to 6.5 - $10^{12}$ GeV with such E-cut, MMC works for energies up to $10^{15}$ - $10^{19}$ GeV, which is mainly determined by the computer precision with which double precision numbers can be added ($\pm 10^{-15}$ - $10^{-16}$). 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 loses the energy, which is why it appears that its losses go up. With fixed cut-off, MMC works for energies up to $10^{15}$ - $10^{19}$ (and apparently as low as $10^{-15}$ - $10^{-16}$), MMC shows no signs of such deterioration.

Phenomenological lepton generation

MMC allows one to generate fluxes of atmospheric leptons according to parameterizations given in [3]. Earth surface (important for detection at depth) and atmospheric curvature are accounted for, and so are muon energy losses and probability of decay. Although [3] provides flux parameterizations, 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 lepton component and extrapolate the results to the desired energy range. One can also add an ad hoc prompt component, specify it as like fluxes of neutrinos of all flavors, or inject leptons with specified location and momenta into the simulation.

Parameterizations of the cross sections

Four bremsstrahlung parameterizations implemented in MMC are shown in the figure below, excluding one. Bremsstrahlung parameterization agrees best with the Keil-Kokoulin-Petrukhin parameterization for muons, and with the complete screening case of electrons, thereby providing the most comprehensive description of the bremsstrahlung cross section.

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 Brezukov-Bugaev parameterization with the hard component or the ALLM parameterization should be selected for photonouclear 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 $E_{\tau}/(\mu_{\tau}c^2) = \mu_{\tau}/(\mu_{\tau}c^2)$; this is the energy per muon deposited by decaying taus in a beam propagating through medium with density $\rho$). In [2] we compare the average range of taus propagated with $\mu_{\tau} = 0.14$ cm (completely continuously) and $\mu_{\tau} = 0.70$ cm (detailed stopping) to corresponding electromagnetic 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 $1/r^2$) are scaled up with a factor $1/r$, where $r = 1/(2\mu)$ is the monopole charge.

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 $\nu_\tau \rightarrow \nu_\tau$ 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 figure below (also showing the LPM suppression of cross sections). For tau propagation Brezukov-Bugaev parameterization with the hard component or the ALLM parameterization should be selected for photonouclear 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 $E_{\tau}/(\mu_{\tau}c^2) = \mu_{\tau}/(\mu_{\tau}c^2)$; this is the energy per muon deposited by decaying taus in a beam propagating through medium with density $\rho$). In [2] we compare the average range of taus propagated with $\mu_{\tau} = 0.14$ cm (completely continuously) and $\mu_{\tau} = 0.70$ cm (detailed stopping) to corresponding electromagnetic 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 $1/r^2$) are scaled up with a factor $1/r$, where $r = 1/(2\mu)$ is the monopole charge.

MMC implementations

MMC was used in the data simulations of the AMANDA, IceCube, Frejus, 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++ 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 [3] provides an adequate description of data in simulations and studies of systematic uncertainties of several experiments.

References