Muons and Neutrinos at High-Energy Accelerators *

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Abstract

Background levels in detectors and radiation problems at future colliders—whether pp, e^+e^- or $\mu^+\mu^-$—are in large part determined by the presence of muons. Neutrinos from muon decay at muon colliders or storage rings are highly collimated and propagate outward within a narrow disk in which significant radiation doses persist out to very large distances. This paper highlights physics models and Monte Carlo algorithms developed mainly for studying these problems as well as some typical results.

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1 Introduction

High Energy Physics codes do an excellent job of simulating interactions of elementary particles with nuclei and electrons which occur in a detector and its immediate environment. HEP experiments demand that the detector geometry be represented in great detail and require events to be simulated in analog fashion. This is necessary to discriminate against spurious signals as well as to study fluctuations and correlations. But the same reasons make such codes less suited for studying a host of problems which need only *averaged* results for their resolution, e.g., radiation environment and generic detector backgrounds. Although there is a lot of common ground between these two approaches, radiation oriented codes can take advantage of weighted Monte Carlo (MC) algorithms—based on inclusive reaction cross sections *vis-a-vis* full event generators—and of simplified descriptions of the geometry and magnetic environment. This results in great savings in programing effort and execution times. Note, however, not all fluctuations can be ignored in radiation type problems, e.g., fluctuations in energy loss and multiple scattering of muons traversing soil largely determine the spatial distribution of radiation dose. At high energy hadron and lepton colliders muons often determine background and radiation levels. With new proposals for muon colliders ($\mu\mu C$) and storage rings (μSR) actively under study, muons and—surprisingly—neutrinos play an increasingly important role in radiation physics problems. This paper briefly summarizes our recent work in this area.

2 Muon Production

Muons are produced in *hadronic* cascades mainly via decay of pions and kaons. If space is present to allow mesons to decay before interacting, this decay will tend to dominate all other muon production. In a solid target 'prompt' muons may play a more important role. The physical model [1] for the prompt component includes muons from *D*-mesons, vector mesons ($\rho, \phi, \omega, J/\psi$), η, η'-mesons along with production via Drell-Yan and low mass continuum annihilation. Muons are less plentiful in *electromagnetic* showers (EMS): Bethe-Heitler $\mu\bar{\mu}$ pairs with lesser contributions from vector mesons produced by γA interactions and positron annihilation. There is coupling between both types of cascades: generation of EMS via decay of π^0 produced in hadronic cascades and conversely—but to a much lesser extent—from hadrons produced in γA interactions. At lepton machines muons from EMS obviously dominate.

3 Muon Interactions

Ionization Energy Loss. The conventional approach to muon energy loss due to atomic excitation and ionization assumes it occurs continuously at a rate equal to the mean stopping power for charged particles in the material traversed. In certain situations fluctuations may be important since they affect the energy subtracted from the muon, the number of energetic electrons (δ-rays) produced in the material, or muon energy-angle correlations introduced by close μe^- encounters. To include these fluctuations and correlations in the MC an energy-transfer cut-off, ε_c, is introduced. Events below ε_c are treated collectively as a continuous, 'restricted' energy loss, above it events are treated by simulating individual μe (Bhabha) scattering with full energy-angle correlation [2, 3]. Even the restricted energy loss is subject to fluctuations, which depends on ε_c, and follows a Vavilov-type distribution [2]. The latter is difficult to evaluate and to sample from in the MC but it approaches a Gaussian with decreasing ε_c. Independent of energy, material or thickness traversed, the quality of the Gaussian approximation is governed by the average number of events (κ_n) one chooses to evaluate individually and becomes acceptable for most purposes when $\kappa_n > 10$ [3]. A modified Gaussian (Edgeworth series) provides a better fit at all values of $\kappa_n \geq 1$ and retains ease of MC sampling [4]. The number of events simulated is chosen from a Poisson distribution with mean of κ_n.

Coulomb Scattering. The conventional approach to multiple Coulomb scattering assumes a Gaussian distribution in projected angle with zero mean and standard deviation dependent on muon momentum and material traversed. It can be shown that the Gaussian increasingly underestimates the tails of the distribution beginning at about 2σ [5]. A more accurate treatment is provided by the Moliere distribution. However, nuclear form factors must be included [6] to describe the correct angular distribution. These objections may be overcome by an approach similar to that of muon energy loss: below cut-off, θ_c treat all events collectively while those with $\theta > \theta_c$ are treated individually. With decreasing θ_c the collective distribution approaches a Gaussian while selection of individual events (Rutherford scattering with form factor) is easily adapted to MC selection. Here also using the Edgeworth series instead of the Gaussian significantly improves accuracy and/or reduces the number of events to be treated individually [4]. The Edgeworth series is considerably simplified here by the symmetry of the underlying distribution about zero. In both collective and event-by-event treatments, scattering of muons with atomic electrons must be included in a manner consistent with the ionization loss algorithms. The difference between electron and nuclear mass strongly affects the kinematics of individual collisions.

Radiative Processes. For muons with energies above a few hundred GeV, bremsstrahlung and direct e^+e^- production dominate ionization losses especially in heavy materials. Differential cross sections presented in the literature for these processes are too complicated to serve in MC selection routines. Instead these formulae are approximated by parameterizations for which selection is more easily performed [3, 7, 8]. The model [9] used in MARS [10], agrees with experimental data [11] within a few %. In many applications one requires only the cross-section with respect to energy loss and angular deflection of the muon. Where detailed energy deposition is important one also needs approximations to the angle of the emitted photon in bremsstrahlung and of the angles and energy division of e^+ and e^- in pair production [7]. Thereafter these produced particles are traced using MARS. Radiative processes of muons on atomic electrons are also included.

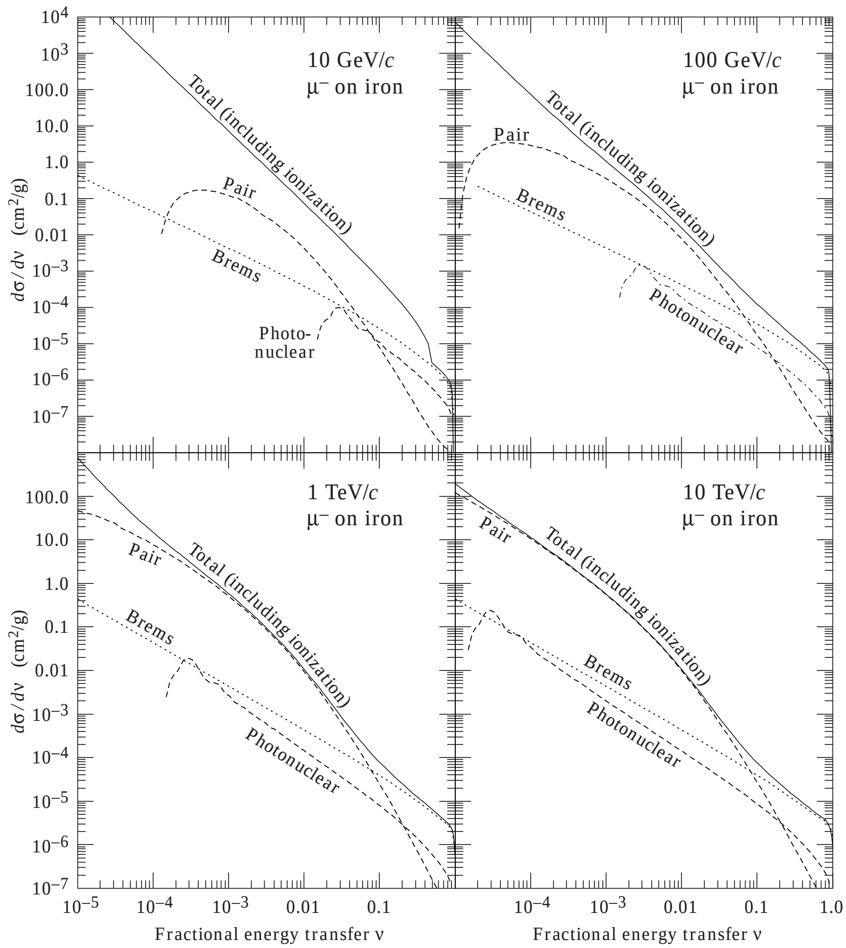

Figure 1: Fractional energy loss probabilities of muons in iron [12]

Deep Inelastic Interactions. As with the radiative processes, simulation of deep inelastic (photonuclear) muon interactions relies on parameterizations of more accurate descriptions. Existing models for this process are consistent only at the 30% accuracy level while the corresponding mean energy loss is at most 10% of the total. Fig. 1 shows the probability of fractional energy loss for high energy muons in iron due to the various mechanisms as calculated with MARS.

4 Muon Radiation

The MARS code serves well to estimate generic backgrounds due to muons in HEP detectors [13] and to study for multi-TeV radiation shielding [14]. To illustrate the latter, Fig. 2(left) shows transversely integrated fluxes in rock downstream of the 7 TeV LHC beam dump of muons and particles produced in their interactions. Hadrons accompanying the muons can be a source of rock and ground-water activation far from the proton beam dump though the rate is rather low. In the LHC arcs—both for operational and accidental beam loss—muons are generated and traced through the lattice elements over about 350 m length. The magnet geometries and the influence of the field in the aperture as well as in the magnet structure results in an interesting pattern of dose contours in the surrounding rock (Fig. 2(right)). Muons are observed as far as 1.5 km outside the ring in the orbit plane where they contribute—along with the accompanying particles—to both dose and radioactivation.

At μμ*C* secondary muons determine radiation shielding in the first tens of meters outward of the tunnel. Where beam is dumped the muons cause a significant dose up to 3.5 km downstream [15]. Hadrons from interactions along the muon tracks produce radionuclides in the soil. For a 2 TeV muon extracted beam ^{3}H and ^{22}Na concentration in ground water within a cylinder 2.5 km long and 2 m in radius could exceed regulatory limits. Therefore, care should be taken to protect any nearby drinking water supplies.

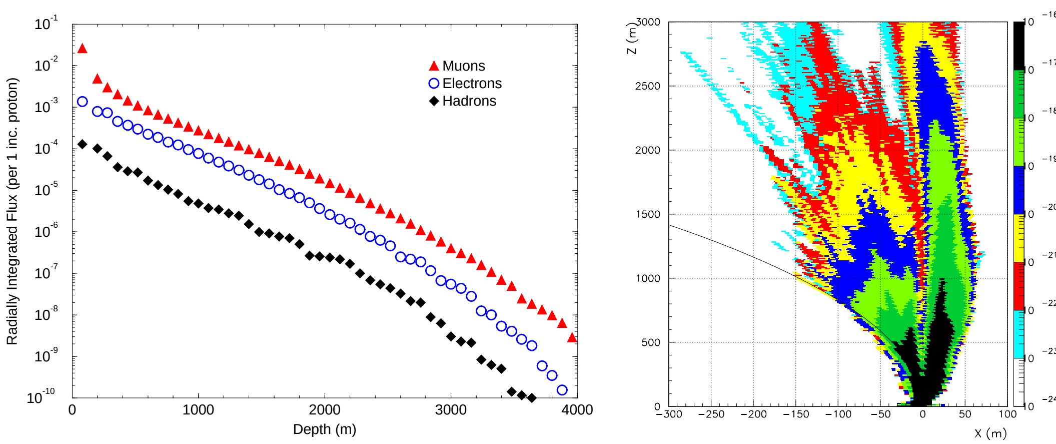

Figure 2: Transversely integrated flux of muons, e^+e^-, and hadrons in rock downstream of LHC beam dump (left) and isodose contours (Sv/proton) in horizontal plane for a 7 TeV beam accident in LHC arc starting at X=Z=0; solid line represents arc

5 Neutrino Interactions

Neutrinos interacting in the human body or its immediate surroundings produce charged particles which may cause biological harm. In simulating these interactions, a neutrino interaction model is called upon which permits selection of energy and angle of each particle: ν, e, μ and hadrons involved in the interaction [16] on an inclusive basis. These particles are then further processed by MARS. The interaction model distinguishes four types of neutrinos ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$) and identifies a number of interactions for each type of neutrino: deep inelastic interactions via both charged and neutral currents, neutrino-nucleon elastic and quasi-elastic scattering where proton and neutron targets (within a nucleus) are distinguished, neutrino interactions with atomic electrons, and coherent elastic scattering off a nuclear target. All these interactions produce a lepton (ν, e, or μ) in the final state. To first approximation, the formulae for the energy and angle of the lepton are simple enough for use in MC selection. Once selection of the lepton is made, (vectorial) momentum is balanced by imparting the missing momentum to the target nucleon, nucleus or electron. For deep inelastic scattering momentum is balanced by a single π which is then forced to interact in the target nucleus after which the reaction products are followed by MARS.

6 Neutrino-Induced Radiation

So far, in all cases studied where neutrino induced radiation may be a problem, the 'source' of the neutrinos is a $\mu\mu C$ or μSR so that energy and direction of the decay ν are readily obtained. These neutrinos propagate almost tangentially to the muon direction in a relatively narrow disk with negligible attenuation. Dose at a given location grows with muon energy roughly as E^3 due to three factors: increase with E of the neutrino interaction cross section and of total energy deposited while the decay angle decreases roughly as m_μ/E. Transverse dimensions of the neutrino disk may be smaller than human dimensions and one must distinguish between *maximum* and *whole body dose* which has legal as well computational ramifications. A useful concept is that of *equilibrium* dose, i.e. dose is proportional to neutrino fluence in the vicinity of its maximum. This applies when a minimal thickness of material (a few meters of soil or equivalent) is present immediately upstream of the 'phantom' to which dose is delivered so as to allow the ν-induced cascades to develop fully in the material. The 'non-equilibrium' dose, calculated for a bare phantom, is much less than the equilibrium dose—a factor of three at 1 GeV and up to three orders of magnitude for 10 TeV neutrinos. Neutrino doses become surprisingly large for some of the more ambitious muon devices contemplated. For proposed μSR located underground, the off-site dose limit of 0.1 mSv/yr is met 50 m outward from the arc tunnel, but downstream of a 600-m long straight section only at 1.8 and 4.2 km for the 30 and 50 GeV μSR, respectively (Fig. 3(left)). Fig. 3(right) shows the large distances (up to 60 km) required to reduce neutrino dose to acceptable levels around a high energy μμ*C* if no other precautions are taken.

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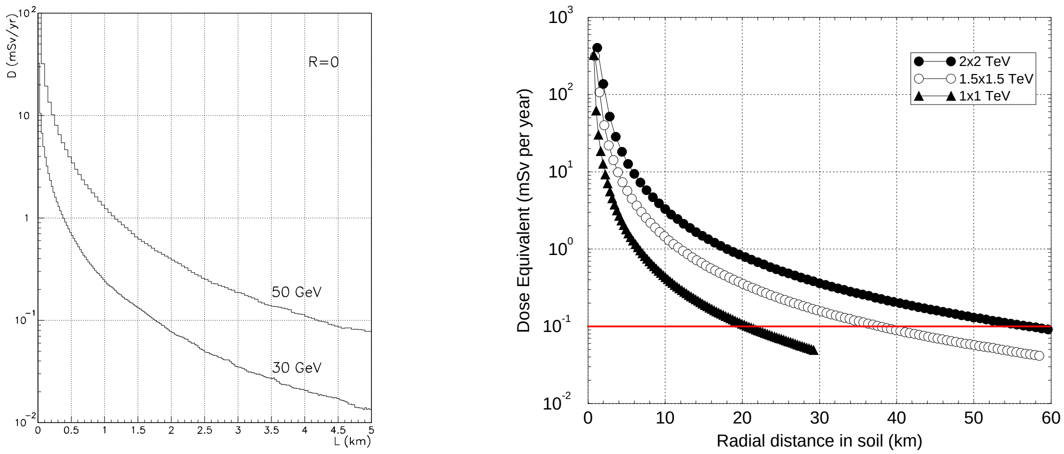

Figure 3: Annual maximum dose equivalent (mSv/yr) in a phantom embedded in soil *vs* distance downstream of 30 and 50 GeV μ*SR* straight sections (left) and in a μμ*C* orbit plane with 1.2×10^{21} decays per year *vs* distance from ring center (right)

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