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Air shower simulation for background estimation in muon tomography of volcanoes

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Abstract

One of the main sources of background for the radiography of volcanoes with atmospheric muons comes from the accidental coincidences produced in the muon telescopes by the air showers. In order to quantify this background, Monte-Carlo simulations of the showers and of the detector are developed by the TOMUVOL collaboration. As a first step, the atmospheric showers were simulated and investigated using two Monte-Carlo packages, CORSIKA and GEANT4. We compared the results provided by the two programs for the muonic component of vertical proton-induced showers at three energies: 1, 10 and 100 TeV. We found that the spatial distribution and energy spectrum of the muons were in good agreement for the two codes, while significant differences were observed for the arrival time of the muons.

1 Introduction

Two aspects of muon tomography of volcanoes make relevant, if not necessary, the use of Monte-Carlo simulations in order to obtain an acceptable precision in the imagery. The first point is the fact that we want to evaluate accurately the attenuation of the flux of atmospheric muons crossing the volcano. To this end, the incident flux of muons has to be well described and analytical approximations cannot easily account for it accurately enough at low energies and for nearly horizontal muons. The atmospheric muon flux depends not only on the altitude and on the zenith angle of the muons, but also on their energy, which is generally not measurable with the experimental setups of the present tomography experiments. Also, for low energy muons (below few GeV), the Earth magnetic field induces a dependence of the flux with the azimuth.

The second argument in favour of developing such Monte-Carlo simulations comes from the intense atmospheric background the detector is exposed to while performing the tomography. Various particles produced in air showers can hit the detector coherently, creating accidental coincidences and faking the passage of a muon through it.

Due to the randomness of those events, the frequency at which they occur and the characteristics of the induced tracks are very hard to determine analytically.

In this context, a detailed Monte-Carlo study of the atmospheric muon flux is being conducted in TOMUVOL (Niess, 2012). As a first step, a simulation of high energy protons interacting with the atmosphere and creating showers was performed using GEANT4 (Agostinelli et al., 2003). After briefly reviewing here how the atmospheric muons are created during the development of air showers, we present the simulation code in development within the TOMUVOL collaboration, in the framework of GEANT4. Then, the muonic component of the vertical showers induced by protons of 1, 10 and 100 TeV, simulated with GEANT4, is compared with the muonic component of similar showers simulated with CORSIKA (Heck et al., 1998). Corsika is a dedicated software for the simulation of atmospheric showers over a very large energy spectrum, widely used in cosmic ray experiments.

2 The physics of air showers

Cosmic rays are particles, mostly protons (∼ 88 %) and helium nuclei (∼ 10 %), originating from various (extra)galactic sources that come and interact in our atmosphere. Doing so, the most energetic component of their flux initiates events called *air showers*, i.e. extensive cascades of particles collimated in the direction of the incident cosmic particle. The interaction of the incoming cosmic particle with an atmospheric nucleus is characterised by the fragmentation of the nucleus and the creation of a number of secondary hadrons. These can, if energetic enough, experience in turn inelastic interactions with others atoms, or decay into hadrons, photons or leptons. In this scheme, the atmospheric muons (Gaisser, 2012) used in tomography are mostly coming from the decays of two kind of hadrons: charged pions and kaons. As pions constitute the most important part of the hadronic component of the showers, and since the charged ones decay almost exclusively into muons, their contribution is dominant. It is worth mentioning that in addition to the hadronic decays described above, a tiny fraction of atmospheric muons is created by the conversion of photons into a pair of muons. The charm contribution through the decay of η, D's and Λ_c particles (the so called prompt contribution) does not become important until very high energies and will be neglected here (Costa , 2001).

The processes contributing to the muon flux are given below with the corresponding life-times and branching ratios:

$$\pi^{+-} \rightarrow \mu^{+-}\nu_\mu \left(\tau \approx 2,6 \times 10^{-8}\,\mathrm{s}|\mathrm{B.\,R.} \approx 100\,\%\right)$$

$$K^{+-} \rightarrow \mu^{+-}\nu_\mu \left(\tau \approx 1,2 \times 10^{-8}\,\mathrm{s}|\mathrm{B.\,R.} \approx 64\,\%\right)$$

$$K^0_\mathrm{L} \rightarrow \pi^{+-}\mu^{-+}\nu_\mu \left(\tau \approx 5,1 \times 10^{-8}\,\mathrm{s}|\mathrm{B.R.} \approx 27\,\%\right)$$

$$\gamma \rightarrow \mu^+\mu^-.$$

The developement of the hadronic showers depends not only on the energy and on the type of the incoming cosmic ray, but also on the amount of matter the cosmic particle will cross when propagating in the atmosphere. The secondary particles created in the shower lose themselves part of their energy when propagating. As an example, high energy pions tend to interact before decaying leading to less higher energy muons being created: the muon high energy spectrum steepens.

Although the muons will interact only relatively weakly with the atmosphere, they also lose a small fraction of their initial energy until they reach the ground, where they are detected. In the case of horizontal muons, the very long path they have to travel in the atmosphere until ground leads to significant energy losses and an important fraction of the low energy horizontal muons decay before reaching the ground. This is the reason why the energy spectrum of the horizontal muons is much flatter than in the case of the vertical muons.

We see that a multitude of physical processes are involved between the arrival of a cosmic particle at the top of the atmosphere and the detection of a muon at ground level. These processes are of stochastic nature, and will occur many times in average for each event. Thus, to extrapolate the expected muon flux at detection level from the – relatively well-known – primary cosmic ray flux, the use of Monte-Carlo simulation tools seems to be a convenient way to go. In the next sections, the efforts made in TOMUVOL to develop such a Monte-Carlo simulation are presented.

3 Simulation of air showers using GEANT4

GEANT4 is a widely used simulation software, designed to simulate the interaction of particles with matter in a fully customizable environment. The advantage of this program in the context of muon tomography is the possibility to describe in the same simulation framework the development of air showers, the interactions of the muons in the volcano, and finally their detection. Such a code is currently in development within the TOMUVOL collaboration, and we focus here on the part dealing with the development of air showers.

The setup of the simulation at present day consists of an atmosphere modelised with 1960 spherical layers of air, with temperature and density set according to the *mid-latitude winter* model (Kneizys et al., 1996). This data model is also currently used in CORSIKA. At the top of the atmosphere, vertical protons of predefined energies are shot and let to interact with the air molecules. The physics list used is QGSP_BERT (GEANT4 Collaboration, 2012; Apostolakis et al., 2010; Dotti, 2011), which is standard in several high energy physics experiments, completed with the $\gamma \rightarrow \mu^+ \mu^-$ process. The output of the code is a file containing the information about the particle flux at an altitude of 870 m, which is the current TOMUVOL detector operation altitude in front of the Puy-de-Dôme.

One of the features of GEANT4 is that each particle carries information about its creation. In particular, it is possible to know the nature of the particles which created the muons crossing the plane $z = 870$ m. As an example, the energy spectrum of the muons created in showers initiated by 10 TeV incident protons is given in Fig. 1 for all the different production channels active in our physics list. As a very general observation, one can say that the relative contributions from the different possible mother particles agree with expectations. At this point, and before extending the simulation to the generation of an inclusive cosmic ray flux, a more accurate check of the generated muon fluxes is needed. In order to do so, the code was tested by comparing its results with those from another simulation software: CORSIKA.

4 Comparison with CORSIKA results

CORSIKA is a program specifically designed for the simulation of air showers, commonly used in this field and which has been improved for decades, as new experimental data on air showers were obtained. Therefore, the results provided by this program will be considered as a reference in this study. In order to validate our GEANT4 code with respect to the simulations of CORSIKA, the atmospheric muons fluxes recorded at an altitude of 870 m (a.s.l.) in both programs were compared. The GEANT4 data which have been used corresponds to vertical proton primary particles of energies 1, 10 and 100 TeV. In CORSIKA we simulated a realistic cosmic ray spectrum, over the full energy and zenith angle ranges and including also Helium nuclei. To have a meaningful comparison with the GEANT4 simulation, we restricted the CORSIKA sample to showers with zenith angles less than 10° and energies within 10 % of the corresponding energy of the GEANT4 showers. Note that a cut on the energy of the muons, $E_\mu > 10$ GeV was applied, so the effects of the earth magnetic field, not yet included in our GEANT4 code but present in CORSIKA, could be neglected.

The muons at $z = 870$ m were characterised by three variables: their energy and their spatial and temporal distributions within the shower. The energy spectrum of the muons (the number of entries in the histogram is normalised to the number of muons present in the shower) are shown in Fig. 2 for both GEANT4 simulation and CORSIKA and the agreement is good.

For the spatial distributions, the mean centre of gravity of all the muons in the shower at the $z = 870$ m plane was subtracted from the position of each individual muon, such that the normalised spatial distributions shown in Fig. 3 are centred on zero. Again, there is a reasonable agreement between the GEANT4 and CORSIKA simulations, though CORSIKA displays a slight tendency towards wider high energy showers.

A significant discrepancy is observed for the time profiles of the showers (Fig. 4). Indeed, the CORSIKA distributions look more peaked that the GEANT4 ones, an effect which increases with the energy of the primary. This effect needs to be investigated because the number of accidental coincidences induced by the showers in the muon telescope depends on the time distribution of the particles reaching the detection level.

5 Conclusions

The first step toward the Monte-Carlo study of atmospheric background in muon tomography is the simulation of the air showers. A choice has been made in TOMUVOL to develop such a program in GEANT4, since the next stage of this work should involve the simulation of the detection of the particles in the telescope, which GEANT4 is designed for. In order to validate the part of the code related to the showers simulation, the muon fluxes at an altitude of 870 m that we obtained with vertical 1, 10 and 100 TeV primary protons were compared to those from a well-tested air shower simulation software: CORSIKA. We found that the lateral and energy profiles of the muons were in agreement in both codes, while significant discrepancies for time profiles appeared. That point is to be investigated, but, nevertheless, GEANT4 seems well-suited for the simulation of the showers. The extension to the generation of an inclusive cosmic ray flux inside GEANT4, together with the detector description, should allow us to extract results on the amount and direction of contamination of the accidental coincidences that should be expected in our detector configuration.

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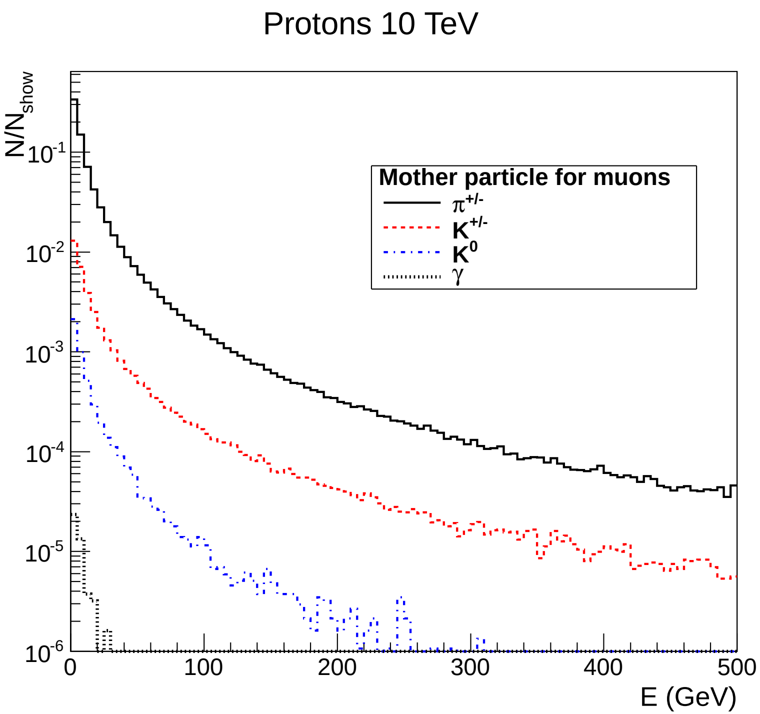

Fig. 1. Energy distributions of the muons from showers initiated by 10 TeV vertical protons at an altitude of 870 m, as simulated in GEANT4. The contributions from the different mother particles are dissociated: pions (solid line), charged kaons (dashes), neutral kaons (dot dashes), gammas (dots). The vertical axis indicates the mean number of particles per shower.

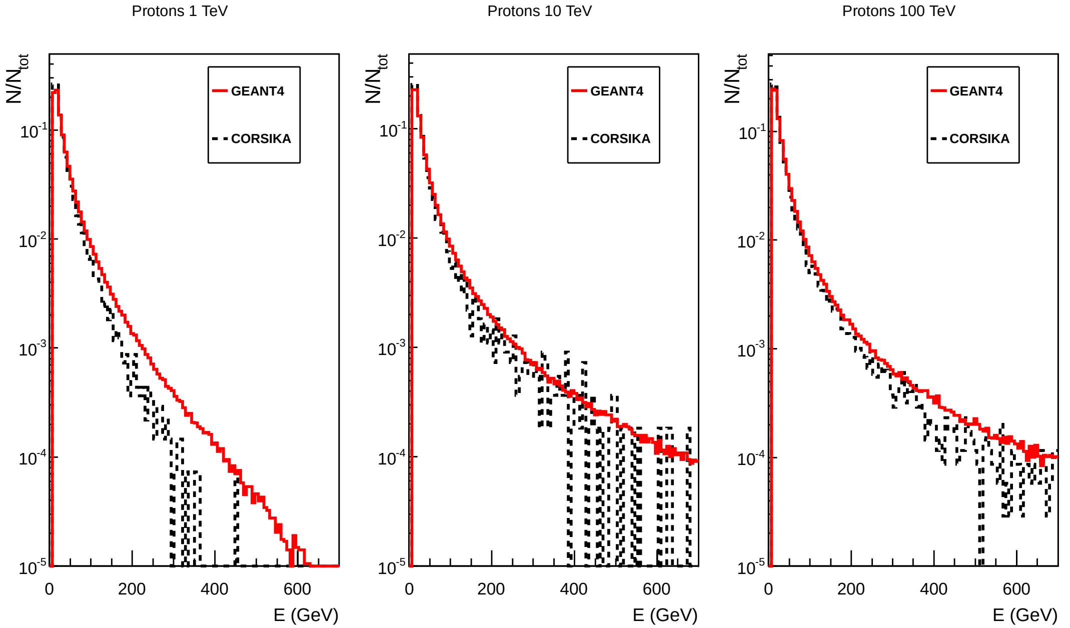

Fig. 2. Energy distributions of the muons at $z = 870$ m as obtained with CORSIKA (dashes) and GEANT4 (solid line), normalised to the number of muons produced in each shower.

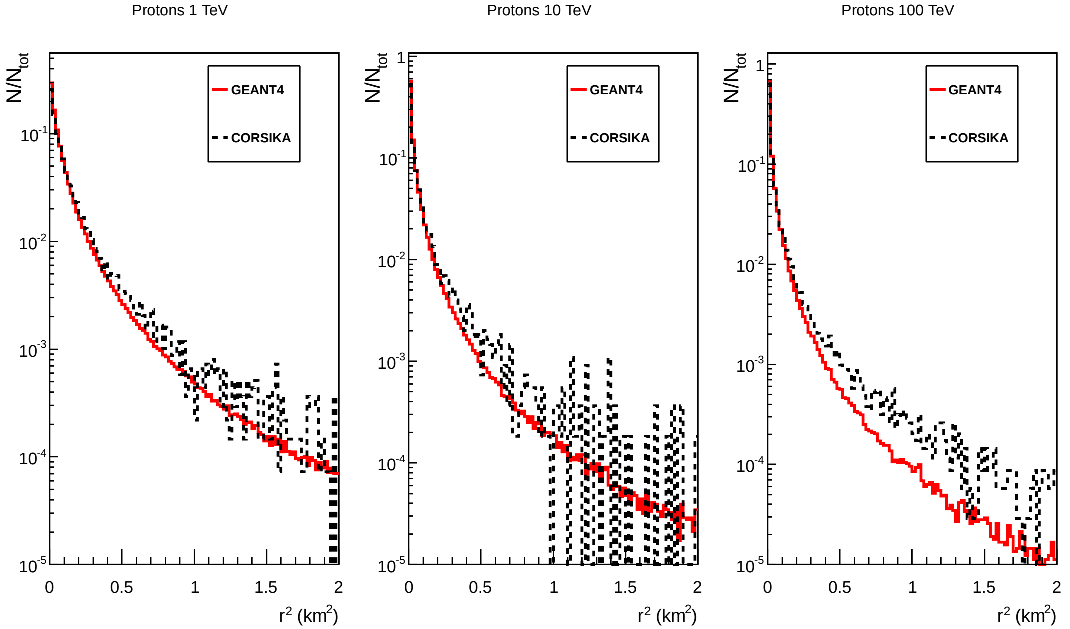

Fig. 3. Lateral distributions of the muons at $z = 870$ m as obtained with CORSIKA (dashes) and GEANT4 (solid line), normalised to the number of muons produced in each shower. r is the distance to the center of gravity of the muons in each shower, computed in the detection plane.

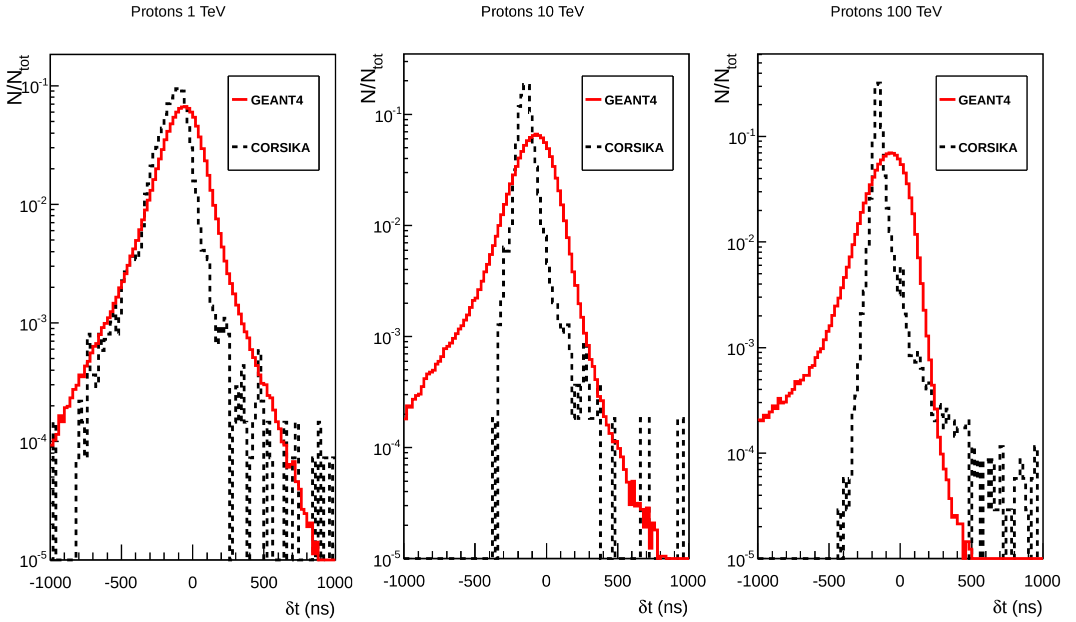

Fig. 4. Time distributions of the muons at $z = 870$ m as obtained with CORSIKA (dashes) and GEANT4 (solid line), normalised to the number of muons produced in each shower. The arrival time is relative to the mean arrival time of the muons in each shower in the detection plane.