Simulation of Multi-muon Events from EAS at Shallow Depths Underground

Dimitri T. Bourilkov*
ETH Zürich, Switzerland

Talk presented at the First Arctic Workshop on Cosmic Ray Muons, Sodankylä, Finland, 24-29 April 1999

Abstract

The Monte Carlo program ARROW, based on GEANT and using GHEISHA at energies below 30 GeV, is developed for simulation of the hadron and muon components of extensive air showers with primary energy $10^{12} - 10^{17}$ eV. Calculations of the characteristics of multi-muon events as observed underground by the LEP detectors are presented and their dependence on the primary cosmic ray composition and some basic assumptions of the hadronic interaction model is discussed.

Introduction

The muon component of extensive air showers (EAS), due to the long muon range in the Earth's atmosphere, carries a wealth of information about the shower development. Study of multi-muon events gives an insight into the primary cosmic ray composition and the physics of high energy hadronic interactions. The LEP detectors, situated between 30 and 150 m underground, offer interesting possibilities to detect and study such events [1–3], which are complimentary to the data collected in traditional cosmic ray experiments. The hadron component of EAS is absorbed, while the muon component is detected with low threshold (typically, if we exclude access shafts, between 15 and 75 GeV) and high momentum and spatial resolution by the sophisticated tracking systems of the LEP detectors. The multi-muon event rate is high enough to make studies of the knee region possible with one year of data taking.

The interpretation of the measurements at the Lake of Geneva level needs a detailed simulation of the interactions of the primary cosmic ray particles with the air nuclei in the upper atmosphere and the consequent shower development through air and the rock overburden of the detectors. Many models are in use, and all of them rely on extrapolations from the existing accelerator data at lower energies. This fact, together with the inherent ambiguity between the inelasticity in the first interactions and the mass composition of the primary cosmic rays, introduces a model dependence in the extraction of quantities of physics interest from the measurements and makes the use of many observables and different models desirable.

*email: dimitri.bourilkov@cern.ch

The Method

In [4] a method for simulation of the hadron component of EAS and the code ARROW are developed. They are based on the well known MC simulation programs GEANT [5] and GHEISHA [6], widely in use in high energy physics. GHEISHA simulates in great detail the nuclear interactions up to $\sim 30 - 50$ GeV. For higher energies up to 10^{17} eV a model based on extrapolations from existing accelerator data on total and elastic cross sections, charged particle multiplicities and leading particle spectra is developed. This allows to study the dependence of key characteristics of EAS on the basic assumptions of the hadronic interaction model. For primary nuclei the superposition model is used. As GEANT defines *only* volumes with constant density, the Earth's atmosphere is modeled with 30 layers, giving a suitable description of the real density profile. The modeling of the overburden and the detector volumes is straightforward.

In this contribution I extend the code ARROW to study the muon component of EAS. Here one can take advantage of the well established tracking capabilities of GEANT. The muonic interactions are simulated up to 10 TeV:

- decay in flight
- ionisation and δ-ray production
- multiple scattering
- bremsstrahlung
- direct (e^+e^-) pair production
- nuclear interactions

making GEANT useful for cosmic ray studies.

Results and discussion

As a case study simulations for the L3 setup are performed for vertical showers initiated by protons or iron with primary energies 1, 10, 100 TeV, 1, 10, 100 PeV. The altitude is 449 m above sea level, corresponding to ~ 980 g/cm^2. All muons which reach the level of the muon chambers of L3 after passing the earth overburden (28.75 m of molasse), the magnet coil and the return yoke are retained for further analysis. The minimum energy at this stage is required to be 2 GeV in order to have good tracks in the chambers. The variation of the muon flux is found to be:

- below 10 % if we vary $\bar{x}_{\mathrm{leading}}$ from 0.25 to 0.30
- increase by 20 % for protons at 1 PeV if we use a fast increase in charged particle multiplicity [4].

The results presented further use the parametrization from [7], which predicts a slow increase of the charged multiplicity and can be considered as a safe lower limit for the expected muon multiplicity.

Primary	P_1	P_2	P_3
proton	0.0129	0.798	0.00
iron	0.0190	0.766	1.04

Table 1: Results of the fit to the ARROW simulations for the total number of muons in EAS initiated by protons or iron with energies from 1 TeV to 100 PeV at L3 level. For protons the threshold factor is set to zero.

Energy PeV	N_μ	R_0 m	N_μ	R_0 m
	proton		iron	
0.01	22	127	18	493
0.1	115	127	270	245
1	750	101	1800	124
10	5200	86	10800	109
100	30700	83	67800	93

Table 2: Results of the fit to the ARROW simulations for the muon density at L3 level as a function of the distance from the shower core.

The total number of muons in the shower above given threshold is parametrized as:

$$N_\mu = A \cdot P_1 \cdot (E/A)^{P_2} \cdot (1 - \frac{P_3 \cdot E_\mu^{thr}}{E/A})^{10}$$

where A is the atomic number and E the total energy in GeV of the primary, E_μ^{thr} is the muon threshold energy, and $P_1,\ P_2,\ P_3$ are free parameters. The results are summarized in Table 1.

The muon density is fitted with the Greisen function ($P_1 = N_\mu,\ P_2 = R_0$):

$$\rho_\mu(r) = 0.2575 * P_1 \cdot (\frac{1}{P_2})^{1.25} \cdot r^{-0.75} \cdot (1 + \frac{r}{P_2})^{-2.5}$$

The results are summarized in Table 2. The two independent fits give similar results for the total number of muons, showing an overall good description of the muon density by the Greisen function. For energies below $\sim$ 100 TeV the χ^2 of the fits is rising, indicating deviations of the muon density closer to threshold from this simple functional form. One can observe that the parameter R_0 is shrinking for higher energies, reflecting a build-up of very high muon densities near the core for more energetic showers. The energy dependence of R_0 is parametrized with a third order polynomial in log(E).

Then a fast simulation of the expected muon multiplicity in the L3 detector (suitable, after the necessary changes, for all LEP detectors) is developed. It is based on the fit results of the detailed simulations with ARROW, using the parametrizations given above. The muon multiplicity is assumed to originate from proton or iron induced vertical showers within 1 srad with E_0 from 1 TeV to 1 EeV. The showers fall up to 1000 m from a detector with idealized geometry and 11 x 11 m^2 sensitive surface. The primary flux is taken from [8] in two limiting cases:

- case A: the knee occurs at the same energy for each primary particle, leaving the composition unchanged in the whole energy range
- case B: the knee occurs at the same energy per nucleon, resulting in an increase of the iron component from 0.3 of the proton component below the knee to 1.5 well above the knee.

One should keep in mind that the parametrizations in [8] contain many components, so the flux used here amounts to 49.5 % of the total primary flux. This is good enough for the exploratory study presented in this talk, but certainly needs to be refined for a confrontation with the real data.

The integrated muon multiplicity is shown in Figure 1.

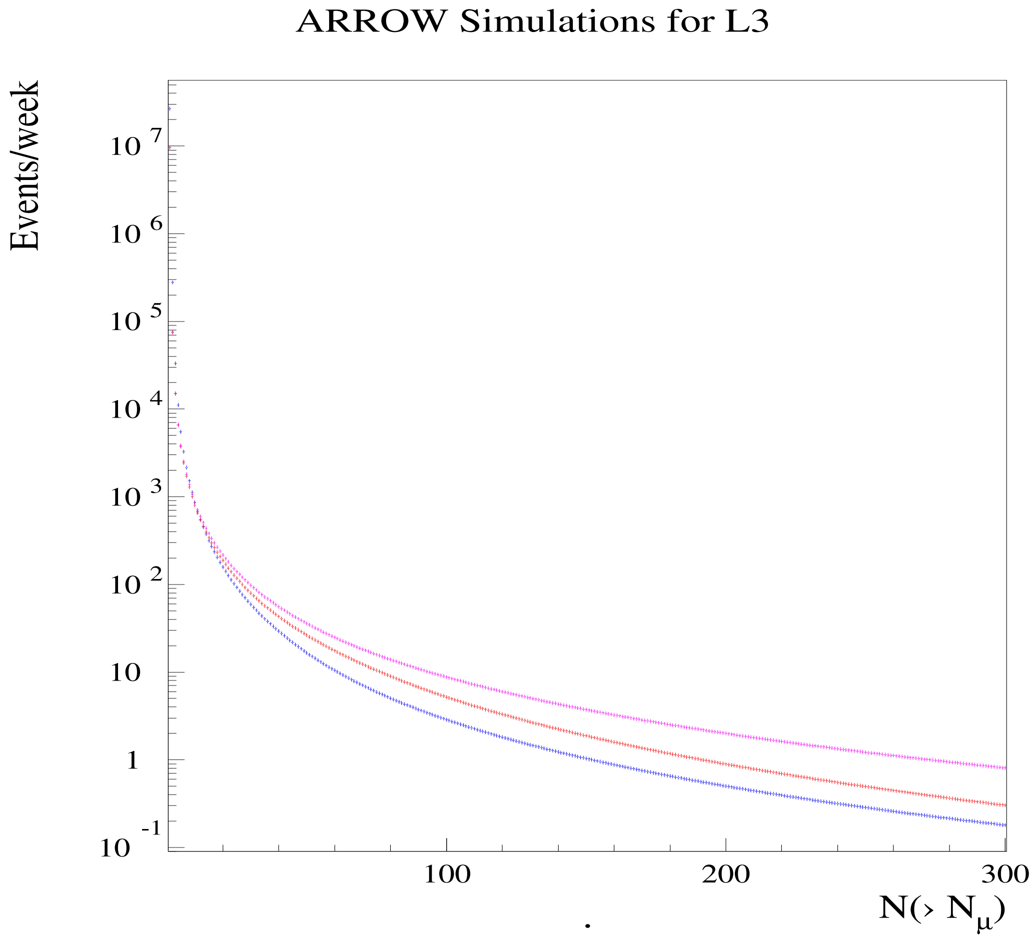

Figure 1: Integrated muon multiplicity - number of expected events with N(> N_μ) for a week of data taking. Lower curve - protons, middle curve - iron: case A, upper curve - iron: case B (see text).

In one week we can expect to see events with more than hundred muons. The distribution is very sensitive to the contribution of the heavy component in the primary flux, as can be observed from the large difference between cases A and B for iron nuclei. A fast increase in the charged multiplicity with energy will also reflect directly in this distribution. In one year sufficient samples from showers above the knee can be accumulated.

Conclusions

The results of this work can be summarized as follows:

- a Monte Carlo method, based on GEANT and GHEISHA, is developed for simulation of the hadron and muon components of EAS
- basic characteristics of muons at shallow depths underground can be computed in three dimensions
- the dependence of the muon flux on some key characteristics of the hadronic interaction model (inelasticity, multiplicity) is investigated
- a fast parametric simulation for the μ multiplicity underground is developed
- the μ multiplicity is a sensitive tool to study the primary composition around the knee
- information about muon momenta and lateral spacing can give additional handles and will be included in more detailed studies
- the real challenge will be to compare the results of simulations with the data expected to be taken by the LEP detectors in the years 1999 and 2000.

Acknowledgements

The author is grateful to P. Le Coultre for the constant support of this studies and to K. Eggert for the invitation to participate in the workshop.

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