STUDY ON MUON FLUX AND RECONSTRUCTION METHODS WITH CORSIKA CODE

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Abstract

We present results of Monte Carlo calculations using CORSIKA [8] code, where we simulate air showers initiated by high energy cosmic rays. The CORSIKA allow one to use, at lower energies, five models for hadronic interactions: SIBYLL [7], VENUS [18], HDPM [6], DPMJET [15] and QGSJET [10]. In order to check CORSIKA results, we compare the prediction of these models to muon flux at sea level to experimental values. Also, we study a procedure to reconstruct events in the surface array of Pierre Auger Observatory, using results from CORSIKA.

1 Introduction

Extensive Air Showers (EAS) are cascades of particles initiated by the interaction of a cosmic ray primary with an atmospheric nucleus. As they develop in the atmosphere, the number of particles increases up to a maximum as a consequence of several hadronic and electromagnetic processes. A detailed theoretical modelling of all these processes is a very difficult problem to be solved, then a Monte Carlo code is needed to describe their features. CORSIKA (COsmic Ray SImulation for KAskade) [8] is a program originally developed to perform simulations for the KASKADE [12] experiment at Karlsruhe and has been refined into a tool that is used by many other groups. It is a detailed simulation of EAS initiated by protons, light nuclei (up to iron), photons and other elementary particles. The particles are tracked through the atmosphere untill they decay or undergo reactions with the air nuclei.

2 Vertical muon flux

At sea level, the muons are the main type of particles that reach a self triggered detector, so we have a big amount of data on vertical muon flux. We tried to reproduce the flux of vertical muons at sea level with the CORSIKA code starting from a primary proton spectrum. According to recent measurements [19], for $E > 10GeV$, the energy spectrum of primary protons is given by a power law:

$$\frac{d\Phi}{dE} = \Phi_0 \times E^{-\gamma} = (1.940 \pm 0.057) \times E^{-2.75 \pm 0.02} (cm^2 s \; srad \; GeV)^{-1}$$

Although this spectrum starts at 10 GeV, we simulated EAS initiated by protons with energies starting at 100 GeV, because the bulk of showers below this energy vanishes before reaching the sea level and their contribution to the muon flux is minimal. We produced 100,000 showers for each high energy hadronic model. The shower energies range from 100 GeV to 10 PeV with diferential spectral index $\gamma = -2.75$ and their zenith angles range from 0^o to 45^o within strips of constant solid angle. Then, we have taken the energy distributions of the muons at sea level weighted by the secant of their zenith angle, for the flux is measured by unit area and the inclined particles observe the surface areas reduced by this factor. To convert from energy distributions to flux, one has to multiply them by the factor:

$$\int_{Ei}^{Ef} \Phi_0 E^{-\gamma} dE = \int_{Ei}^{Ef} \frac{d\Phi}{dE} dE = \frac{Ef^{(1-\gamma)} - Ei^{(1-\gamma)}}{(1-\gamma)} \equiv \Phi$$

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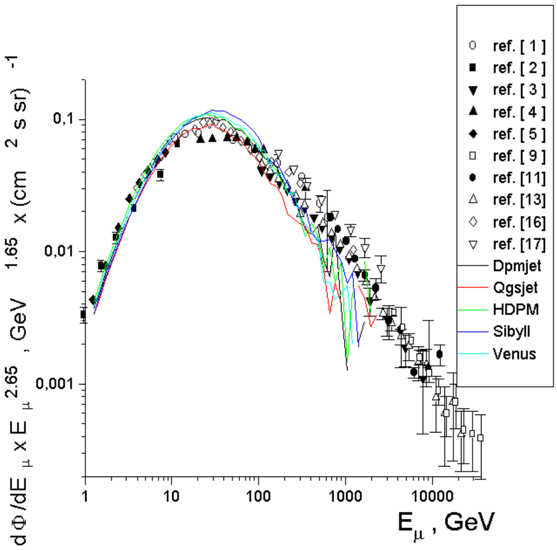


Figure 1: Flux of vertical muons.

In figure 1, we can observe the results of the five models compared to experimental data. This spectrum is flattened by the multiplication of the factor $E^{2.65}$. We found a good agreement between simulated events and experimental data, at energies up to 1 TeV.

3 Reconstruction Methods

We also studied the performance of reconstruction methods for EAS main parameters using the CORSIKA code. The detector arrangement followed the proposed features of the Pierre Auger Obervatory [14] surface array: within the Malargue site we traced several paralel lines spaced by 1.5 km and put in each one an integer number of detectors 1.5 km apart. In the figure 2a, we can see the array with a total of 1552 detectors.

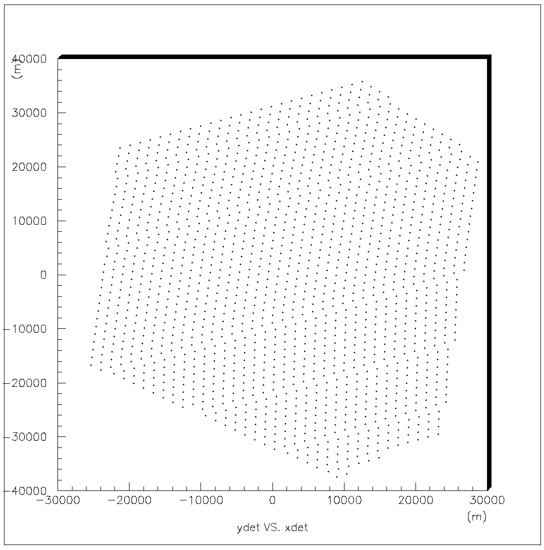
We simulated 90 EAS with fixed primary energy of $E^{20}eV$ (for this energy, one can expect an amount of 60 showers per year), with thinning factor of 10^{-6}. Then we counted the number of observable particles (electrons, muons and photons) with energy greater than 1 MeV hitting tanks of 10 m^2 of area. We considered here ideal detectors, with no signal fluctuations. In the figure 2b, we show the distribution of the number of triggered detectors for all events, assuming 100% of detection efficiency. We found an average value of approximately 5 detectors.

Using the particle countings as input parameters for a χ^2 minimization procedure, we found the core positions (x_0, y_0) and the size (N) at level $880g/cm^2$. The lateral distribution density function is a muonic-like function given by:

$$\rho(r) = \frac{N}{r_0^2} c \left(\frac{r}{r_0}\right)^{-0.75} \left(1 + \frac{r}{r_0}\right)^{-3.5} \qquad , \quad r_0 \simeq 50m$$

The first guess on the core position was given by a baricentre method. The guess on the size is found by inverting the density function for the maximum counting. In the figure 3a we have the correlations in the core abscissas. Notice that we have a RMS of only 33.25 m, indicating a good precision compared to the spacing between the detectors. The events with 2 tanks have not been reconstructed, we need at least 3 densities.

Finally, using the output of sizes we could calculate the primary energy following the parametrization: $E_0 = 10^8 \left(\frac{N}{10^4}\right)^{0.9}$.



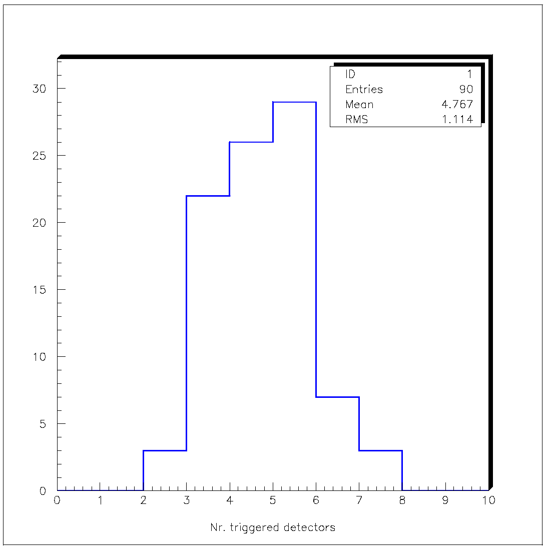
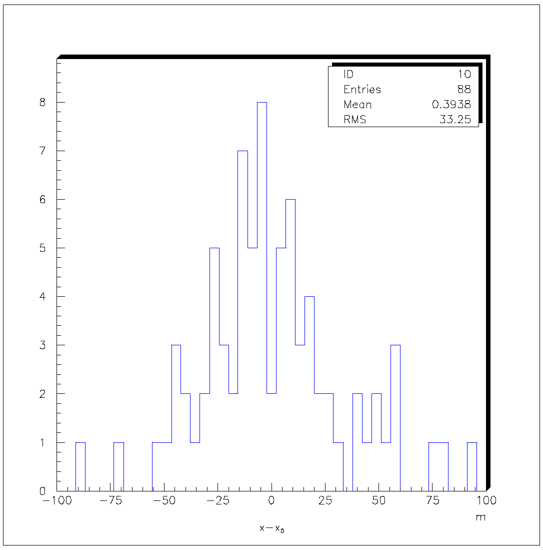


Figure 2: a) Suface array configuration; b) Number of triggered tanks distribution.



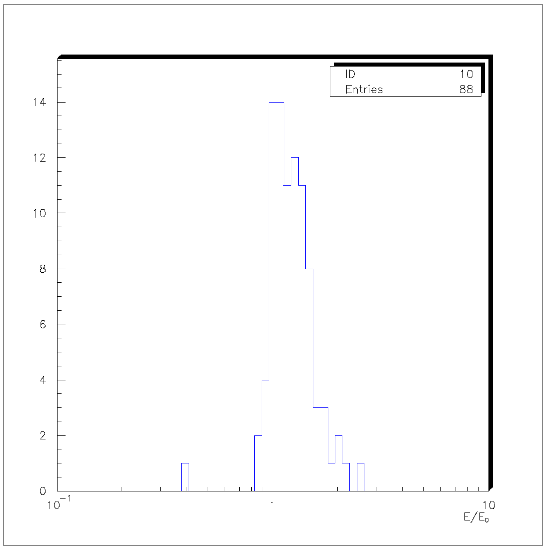


Figure 3: a) Core's abscissa correlation; b) Primary energy correlation.

In the figure 3b, we present the ratio E/E_0, with E being the calculated energy and E_0 the simulated energy. Notice that we have many events approaching the expected ratio, with a tendency of raising the energy outputs. By the figure, we can estimate the precision $\frac{\Delta E}{E} \simeq 30\%$. This would be the primary energy precision of the Pierre Auger Observatory using only the surface array. If the fluorescence detectors were operating, the energy precision should be raised by a factor of 10, but during the day or at moon nights and cloudy skies (90% of total cicle) the surface array is the only energy estimator.

4 Conclusions

We performed a simulation of proton initiated air showers, with CORSIKA package. The primary energies were sampled after a traditional power-law with all available hadronic models. We found a good agreement between measured values of vertical muon flux at sea level, given by several groups and the predictions of CORSIKA, up to 1 TeV. Also we studied some possilbilities for event reconstruction with surface array of Pierre Auger Observatory. We simulated $10^{20}eV$ proton initiated EAS and looked for the lateral distribution of observable particles (e,μ, γ) that hit the water tanks, supposing 100% detection efficiency. By fitting a suitable lateral function to the observable particles, one can make good estimates for core position ($\simeq 33.25m$ uncertainty) and primary energy ($\frac{\Delta E}{E} \simeq 30\%$).

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