

# Air Shower Simulations with the AIRES System

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## Abstract

A report on the characteristics of ultra-high energy air showers simulated with the AIRES program is presented. The AIRES system includes a fast simulating program which is an improved version of the well-known MOCCA program. The AIRES algorithms are briefly described and a series of results coming from the simulations are analyzed.

## 1 Introduction

Cosmic rays with energies larger than 100 TeV must be studied –at present– using experimental devices located on the surface of the Earth. This implies that such kind of cosmic rays cannot be detected directly; it is necessary instead to measure the products of the atmospheric cascades of particles initiated by the incident astroparticle.

A detailed knowledge of the physics involved is thus necessary to interpret adequately the measured observables and be able to infer the properties of the primary particles. This is a complex problem encompassing many aspects: Interactions of high energy particles, properties of the atmosphere and the geomagnetic field, etc. Computer simulation is one of the most convenient tools to quantitatively analyze such particle showers.

In the case of air showers initiated by ultra-high energy astroparticles ( $E \geq 10^{19}$  eV), the primary particles have energies that are several orders of magnitude larger than the maximum energies attainable in experimental colliders. This means that the models used to rule the behavior of such energetic particles must necessarily make extrapolations from the data available at much lower energies, and there is still no definitive agreement about what is the most convenient model to accept among the several available ones (Anchordoqui, Dova, Epele and Sciutto, 1998).

The **AIRES system**<sup>1</sup> (Sciutto, 1999a) is a set of programs to simulate such air showers. One of the basic objectives considered during the development of the software is that of designing the program modularly, in order to make it easier to switch among the different models that are available, without having to get attached to a particular one. The well-known **MOCCA** code created by A. M. Hillas (1997) has been extensively used as the primary reference when developing the first version of AIRES (Sciutto, 1997). The physical algorithms of AIRES 1.2.0 are virtually equivalent to the corresponding ones from MOCCA (Dova and Sciutto, 1997). The structure of AIRES is designed to take advantage of present day computers, and therefore the new program represents an improvement of the MOCCA code, allowing the user to comfortably perform simulations based on the extensive knowledge on air shower processes that is contained in MOCCA's source lines. It is important to remark, however, that the present version of AIRES (Sciutto, 1999a) does include modifications to the original algorithms which can alter the program's output with respect to that from MOCCA. This implies that both programs are no longer strictly equivalent, even if AIRES's physical algorithms continue to be largely based on MOCCA's ones.

Another characteristic of ultra-high energy simulations that was considered when developing AIRES is the large number of particles involved. For example, a  $10^{20}$  eV shower contains about  $10^{11}$  secondary particles. From the computational point of view, this fact has two main consequences that were specially considered at the moment of designing AIRES: (i) With present day computers, it is virtually impossible to follow all the generated particles, and therefore a suitable sampling technique must be used to reduce the number of particles actually simulated. (ii) The simulation algorithm is CPU intensive, and therefore it is necessary to make use

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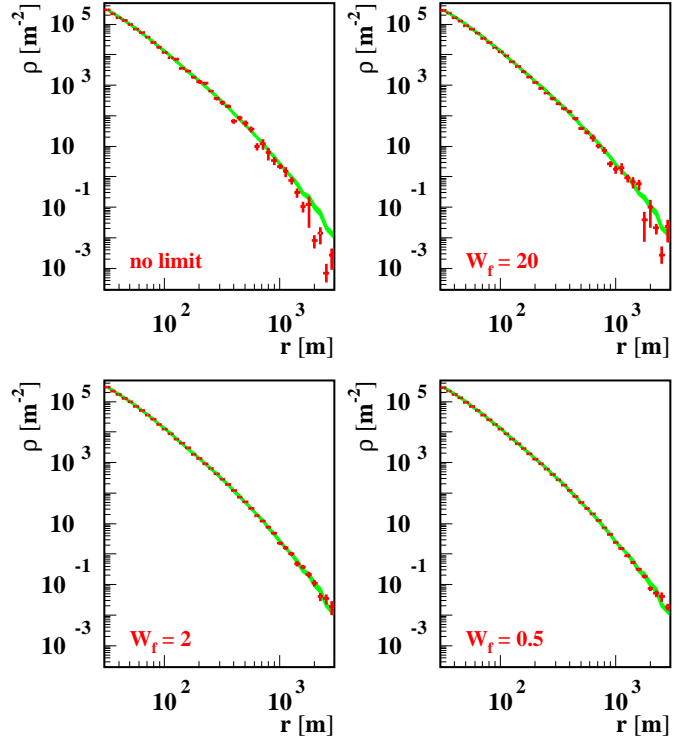
<sup>1</sup>AIRES is an acronym for **AIR**-shower **E**xtended **S**imulations.

of a series of special procedures that will provide an adequate environment to process computationally long tasks.

The particles taken into account by AIRES in the simulations are: Gammas, electrons, positrons, muons, pions, kaons, eta mesons, nucleons, anti-nucleons, and nuclei up to  $Z = 26$ . Electron and muon neutrinos are generated in certain processes (decays) and accounted for their energy, but not propagated. The primary particle can be any one of the already mentioned particles, with energy ranging from several GeV up to more than 1 ZeV ( $10^{21}$  eV).

Among all the physical processes that may undergo the shower particles, the most important from the probabilistic point of view are taken into account in the simulations. Such processes are: (i) *Electrodynamical processes*: Pair production and electron-positron annihilation, bremsstrahlung (electrons and positrons), knock-on electrons ( $\delta$  rays), Compton and photoelectric effects, Landau-Pomeranchuk-Migdal (LPM) effect and dielectric suppression. (ii) *Unstable particle decays*, pions and muons, for instance. (iii) *Hadronic processes*: Inelastic collisions hadron-nucleus and photon-nucleus, sometimes simulated using an external package which implements a given hadronic interaction model (The current version of AIRES includes links to SIBYLL (Fletcher *et al.*, 1994) and QGSJET (Kalmykov, Ostapachenco and Pavlov, 1994) hadronic interaction models.). Photonicuclear reactions. Nuclear fragmentation, elastic and inelastic. (iv) *Propagation of particles*: Curved Earth geometry, losses of energy in the medium (ionization), multiple Coulomb scattering and geomagnetic deflections.

Some of the propagating algorithms and related procedures have recently been revised, and the impact on the shower observables has been studied in detail. The results of such analyses have been reported elsewhere, in particular, in the cases of the LPM effect (Cillis, García Canal, Fanchiotti and Sciutto, 1998) and the external hadronic models (Anchordoqui, Dova, Epele and Sciutto, 1998; Anchordoqui, Dova and Sciutto, 1999).



**Figure 1:** Effect of the AIRES extended thinning algorithm on the fluctuations of the lateral distribution of electrons and positrons.

## 2 Ultra-high-energy showers simulated with AIRES.

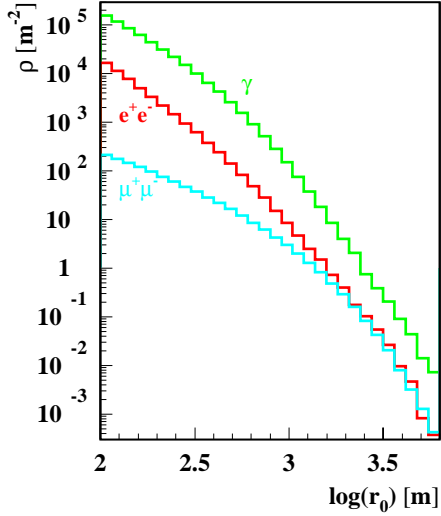
Ultra-high energy showers are commonly analyzed in a shower per shower basis. In the case of simulated data this generally implies generating very detailed data sets to avoid excessive artificial fluctuations due to the sampling algorithm, commonly named *thinning algorithm*.

The AIRES thinning algorithm is an extension of the classical Hillas thinning algorithm (Hillas, 1981). The AIRES extended thinning algorithm (Sciutto, 1999a) permits limiting the maximum statistical weight a particle entry can have by means of an external parameter named *weight limiting factor*,  $W_f$ . The limit  $W_f \rightarrow \infty$  corresponds to the standard Hillas algorithm while  $W_f \rightarrow 0$  completely disables rejection of particles (full sampling).

The plots in figure 1 illustrate how the fluctuations in the electron and positron density (the data correspond to  $10^{19}$  eV vertical proton showers, ground level at 1400 m.a.s.l) behave when the weight limiting factor is modified. The first plot –labelled “no limit”– corresponds to simulations performed with the standard Hillas

thinning algorithm ( $W_f \rightarrow \infty$ ) and  $E_{\text{thin}} = 10^{-5} E_{\text{prim}}$  ( $10^{-5}$  relative thinning level). The lateral distribution for  $10^{-7}$  relative thinning level (also with  $W_f \rightarrow \infty$ ) is also displayed in the form of a continuous shaded band (■) whose width corresponds to the mean value plus or minus one RMS error of the mean. The number of showers is 25 in each case.

The remaining plots of figure 1 correspond, respectively, to the cases  $W_f = 20, 2$  and  $0.5$  ( $E_{\text{thin}} = 10^{-5} E_{\text{prim}}$ ). The shaded band corresponding to  $10^{-7}$  Hillas algorithm –mentioned in the previous paragraph– is repeated in all the plots for comparison. These graphs illustrate clearly how the fluctuations due to the sampling method diminish monotonically with  $W_f$ . In the case  $W_f = 0.5$  they are of the same order than those of the  $10^{-7}$  case, for all the lateral distances plotted, that is, for  $r \leq 2700$  m. Notice also that in this case, the average CPU time per shower for the simulations performed with  $10^{-5}$  relative thinning level with  $W_f = 0.5$  is roughly 11 times smaller than the CPU time necessary to generate one  $10^{-7}$  thinned shower.



**Figure 2:** Gamma, electron and muon lateral distributions corresponding to a single  $3 \times 10^{19}$  eV proton shower simulated with AIRES.

When a relatively low thinning energy is combined with a finite weight limiting factor, the artificial fluctuations due to the statistical sampling method can be dramatically diminished. Such kind of simulations may require large amounts of computer time in certain cases, but they can give a clear enough signal, suitable for detailed simulations of the response of ground detector arrays.

The lateral distributions of gammas, electrons and positrons, and muons corresponding to a single  $3 \times 10^{19}$  eV inclined (zenith angle 45 deg) proton shower are represented in figure 2. The plots correspond to the shower front plane lateral distributions, and  $r_0$  represents the distance to the shower axis measured along this normal plane. The details about the projection procedure will be presented elsewhere (Sciutto, 1999b). The lateral distributions show a low level of noise in all the range  $r_0 \leq 6360$  m, as displayed in figure 2. Notice that the maximum value of  $r_0 = 6360$  m, corresponds to distances to the core up to 9 km, measured along the ground plane.

Global shower observables are also retrieved with a very clear signal. Figure 3 displays the longitudinal development of this single shower being considered.

Figure 3a contains plots of the number of particles versus the slant atmospheric depth for the cases of gammas, electrons and positrons, muons, pions and kaons. The shower maximum (all charged particles) is located at  $847 \text{ g/cm}^2$ ; notice that this shower was simulated using the SIBYLL hadronic package (see Anchordoqui, Dova and Sciutto, 1999).

Figure 3b displays the total energy associated to various particle kinds (divided by the primary energy), plotted as a function of the slant depth. The curve labelled “all” corresponds to the energy of all particles, and equals 1 at the beginning of the shower development, indicating that in this part of the shower development the medium energy losses are very small, and consequently the sum of the energies of the secondary particles is constant. Then, the continuous energy losses become more important and the total energy fraction diminishes monotonically arriving to 0.11 at ground level. The plots for the hadronic secondaries (pions and kaons) clearly indicate the position of the first interaction ( $36.7 \text{ g/cm}^2$ ). Notice that in the early stages of shower development these particles carry a substantial fraction of the available energy, and that a part of this energy is passed to the muons (coming from pion decays), as long as the shower evolves.

### 3 Final remarks

By means of representative examples we have presented some of the main features of the AIRES system for air shower simulations. For more detailed information see Sciutto (1999a).

The AIRES system is still evolving; every new release of AIRES represents a new step towards a complete

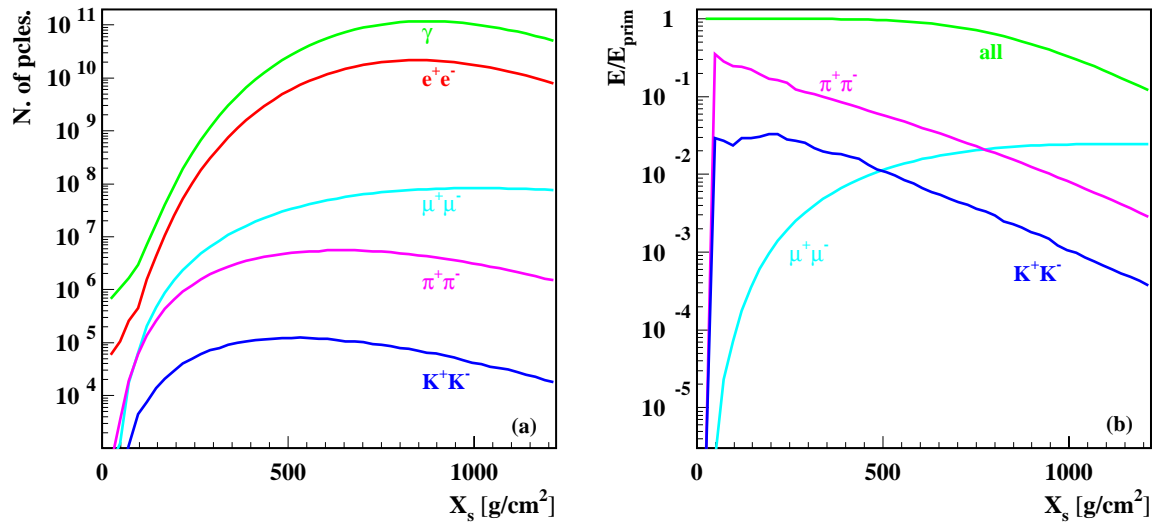


Figure 3: Longitudinal development of a *single*  $3 \times 10^{19}$  eV proton shower simulated with AIRES. In (a) the number of different particle kinds is plotted versus the slant atmospheric depth, while the curves in (b) represent the corresponding total energies (energy longitudinal development), in units of the primary energy.

and more reliable air shower simulation system. There are still many things pending implementation, for example, Čerenkov photon simulation; multiple primary showers; alternative atmospheric models; links to other external packages, especially hadronic models; etc. It is planned to progressively incorporate such additional features. The current status of the AIRES system can always be checked at the AIRES Web page: [www.fisica.unlp.edu.ar/auger/aires](http://www.fisica.unlp.edu.ar/auger/aires).

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