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L. A. Anchordoqui
Northeastern University

G. Cooperman
Northeastern University

V. Grinberg
Northeastern University

T. P. McCauley
Northeastern University

T. Paul
Northeastern University

See next page for additional authors

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Author(s)

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Air shower simulation using GEANT4 and commodity parallel computing

L. A. Anchordoqui^{a*}, G. Cooperman^{b†}, V. Grinberg^{b‡}, T. P. McCauley^{a§}, T. Paul^{a¶}, S. Reucroft^{a||}, J. D. Swain^{a**}, and G. Alverson^{a††}

^aDepartment of Physics, Northeastern University, Boston, MA 02115, USA

^bCollege of Computer Science, Northeastern University, Boston, MA 02115, USA

We present an evaluation of a simulated cosmic ray shower, based on GEANT4 and TOP-C, which tracks all the particles in the shower. TOP-C (Task Oriented Parallel C) provides a framework for parallel algorithm development which makes tractable the problem of following each particle. This method is compared with a simulation program which employs the Hillas thinning algorithm.

1. Introduction

The steeply falling end of the cosmic ray spectrum now extends up to $\approx 3 \times 10^{20}$ eV (see Ref. [1] for a recent survey), three orders of magnitude higher than the highest energy achieved by hadron colliders. Direct measurements using sophisticated equipment on satellites or high altitude balloons are limited in detector area and in exposure time. Ground-based detectors with large apertures make such a low flux detectable after a magnification effect in the upper atmosphere. Namely, the incident cosmic radiation interacts with atomic nuclei of the air molecules and produces extensive air showers which spread out over large areas. This indirect method of detection bears a number of serious difficulties in the interpretation of the recorded data. In particular, since many variables are involved the processes describing the shower development are intrinsically complicated, numerical simulation of the giant cascades has to be performed. The most important source of fluctuations in Monte Carlo simulations such as CORSIKA [2] and ARES [3] are the depth and characteristic of the first few inter-

actions, necessarily related to the quality of our understanding of hadronic collisions.

The parts of the shower model which are based on electromagnetic or weak interactions can be calculated with “good accuracy”. The hadronic interaction, however, is still subject to large uncertainties. In recent years, many models of hadronic interactions have been built around experimental results, predominantly of $p\bar{p}$ colliders. Extrapolations to higher energies, to small angle processes, and to nucleus–nucleus collisions have been performed with varying levels of sophistication. In particular, the algorithms of SIBYLL [4] and QGSJET [5] are tailored for efficient operation to the highest cosmic ray energies.⁹ The different approaches used in these codes to model the underlying physics can lead to different results when applied to the same data [7]. Hence, considerable systematic uncertainties remain. In addition, a significant deviation was recently reported in the predictions of ARES and CORSIKA, even when both programs invoked the same hadronic interaction model to account for the first generation of particles [8]. These discrepancies could result from different energy cuts for the hadronic interaction routines, or there may be some discrepancies in the sampling techniques implemented in these programs to reduce the number of gener-

*doqui@hepmail.physics.neu.edu

†gene@ccs.neu.edu

‡victor@ccs.neu.edu

§mccauley@hepmail.physics.neu.edu

¶tom.paul@hepmail.physics.neu.edu

||stephen.reucroft@cern.ch

**john.swain@cern.ch

††george.alverson@cern.ch

⁹It is important to stress that the latest version of DPMJET was improved for operation up to primary energies of 10^{21} eV (per nucleon in the lab. frame) [6]. However, it was not yet efficiently implemented in ARES, nor in CORSIKA.

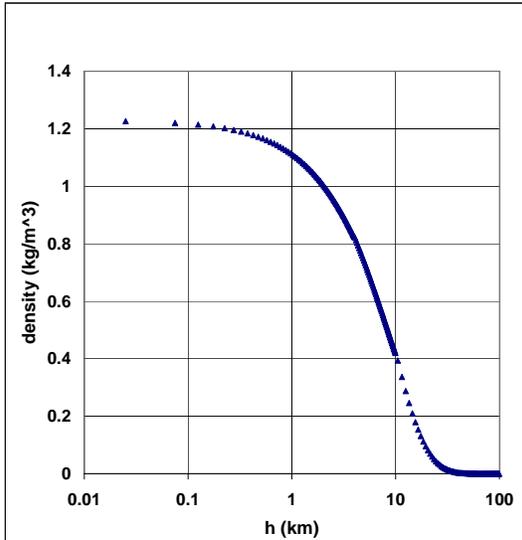


Figure 1. Density of air as a function of the vertical altitude above sea level.

ated particles. We, therefore, considered it worthwhile to compare the simulation results of AIRES (which utilizes the Hillas thinning algorithm [9]) to that obtained with GEANT4+TOP-C [10] (TOP-C makes tractable the problem of following each particle during the atmospheric cascade).¹⁰

2. Air shower simulation

The most direct way to test the predictions of AIRES and GEANT4+TOP-C is to study the characteristics of the secondaries generated under similar conditions. Therefore, in order to reduce possible differences caused by the implementation of hadronic collisions, we analyze the showers induced by 10 TeV protons. Furthermore, we have fixed the energy cuts of GEANT4 according to the default values of AIRES. All shower parti-

¹⁰GEANT4 is the latest stage in the development of the GEANT software, superseding the earlier FORTRAN versions with a new object-oriented approach in C++ [11]. TOP-C (Task Oriented Parallel C) provides a framework for parallel algorithm development [12].

cles with energies above the following thresholds were tracked: 750 keV for gammas, 900 keV for electrons and positrons, 10 MeV for muons, 60 MeV for pions and kaons and 120 MeV for nucleons. The particles were injected at the top of the atmosphere (100 km.a.s.l) and the ground was located at sea level. In the simulations with GEANT4+TOP-C, the atmosphere was defined by a stack of 230 layers of increasing thickness and decreasing density (with the height above sea level). The geomagnetic field was not taken into account. The variable density was modeled using Linsley’s parametrization of the U.S. Standard Atmosphere [13], leading to the density profile shown in Fig. 1. Each point in the figure corresponds to a layer starting with thickness 50 m at sea level and increasing to 1 km at the top of the atmosphere. The above description is consistent with that used in AIRES. QGSJET was used to model the hadronic processes in the simulation with AIRES (we note that at 10 TeV the results obtained with AIRES+SIBYLL are almost the same).

In Fig. 2 we show preliminary results of the longitudinal development of the total number of secondaries that a 10 TeV proton may produce after cascading in the atmosphere. We also show the longitudinal development of different groups of secondary particles (we have considered separately γ , e^\pm , and μ^\pm).

At 600 g/cm² the ratio between the total number of particles produced by GEANT4 and the total number of particles produced by AIRES is ≈ 2 . This ratio increases as the shower front gets closer to the ground, and roughly reaches the value of 4 at 800 g/cm². The main reason for this divergence comes from a difference in the number of charged pions produced during the shower development. In the first generation of particles (governed by the hadronic interaction) GEANT4 produces more charged pions than AIRES. Consequently, in the first steps, the muon shower profile develops faster in GEANT4 than in AIRES.

The photopion production threshold is at a photon energy of 145 MeV in the proton rest frame, with a strongly increasing cross section in the region of the Δ resonances, which decay into neutral and charged pions. With increasing energy photon-proton collisions are no longer me-

diated by resonances, but by the diffractive production of the vector mesons, ρ and ω , or direct multi-pion production. We are currently evaluating whether the physical models available in GEANT4 are sufficient to describe photon-nuclear interactions in the energy range of interest. We note that GEANT4 provides a framework for introducing new physical models if need be. Though our (GEANT4) simulation produces γ 's above the photopion threshold, we observe no charged pions from this process. Therefore, as the shower front approaches the ground, the neutral pion decay channel dominates the cascade, yielding a huge number of electrons and positrons. As a result, the total number of particles is increased, and the position where the shower develops the maximum number of particles is shifted to greater depths.

3. Final Comment

The above comparison between AIRES and GEANT4 is not yet complete. A detailed discussion including the geomagnetic field effects, study of the γp -interaction, and the analysis of different kinds of primaries at "Auger energies" [14] will be given in a future publication.

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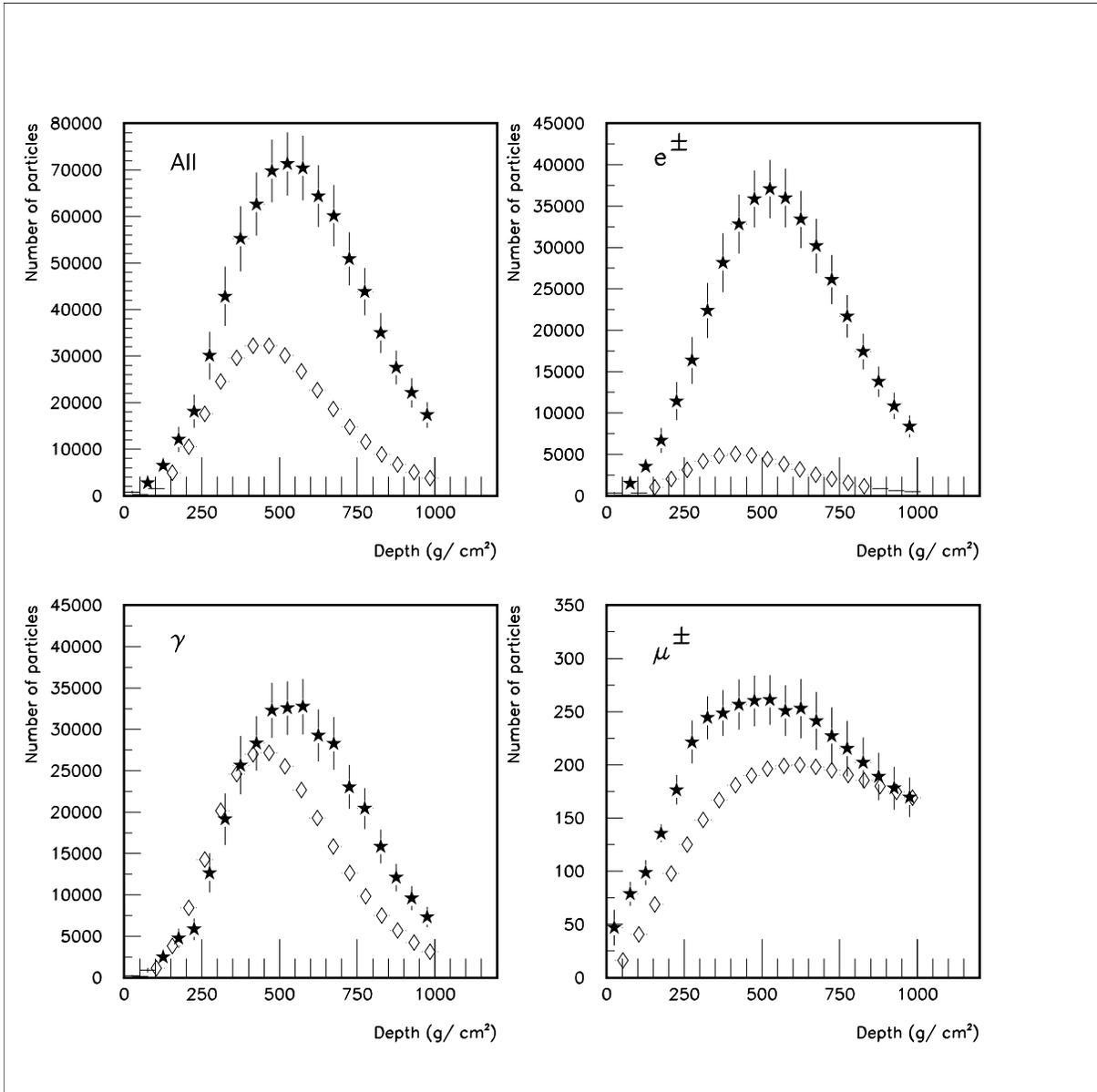


Figure 2. Longitudinal profiles of different secondary species predicted by AIREX (\diamond) and GEANT4 (\star), for showers induced by protons of 10 TeV.