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Study of model dependence of EAS simulations at E $\geq 10^{19}$ eV

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Abstract. Air shower simulation programs are essential tools for the analysis of data from present and future cosmic ray experiments, since estimates of energy and mass of the primary particle can only be obtained by comparison to model predictions, and the model uncertainties translate directly into systematic errors in the energy and mass determination. While the main uncertainty of contemporary models comes from our poor knowledge of the (soft) hadronic interactions at high energies, also electromagnetic interactions, low-energy hadronic interactions and the particle transport influence details of the shower development. We report here on a comparative analysis of simulations for 2×10^{19} eV protons, performed with the AIRES and CORSIKA air shower simulation programs. The model dependency of the main shower observables is discussed. We study also some aspects of the technical performance of both programs.

1 Introduction

Ultra high energy cosmic rays (UHECRs) pose some of the most exciting problems in modern astrophysics. It seems certain that cosmic rays with $E > 10^{20}$ eV exist and reach the Earth at a flux of about 1 per km^2 and century (≈ 15 events in 35 years), yet no astrophysical object is known that could accelerate CRs to those energies. If the sources are distributed on cosmological distances one would expect to see a marked cut-off at about 6×10^{19} eV in the energy spectrum due to reactions of the UHECRs with the microwave background, but no such cut-off is seen by experiments so far. If the sources are nearby, as indicated by the absence of the cut-off, one could expect to see anisotropies in the arrival direction of the particles. At present, however, any investigation of this lacks statistics. Over the last few years many theorists have attempted to explain this enigma with new particles, new physics or exotic phenomena, such as decaying topological defects, or the violation of Lorentz invariance. A solution to the problem can only come from an increase in statistics at highest energies. The precise form of the energy spectrum, the whole-sky arrival direction distribution and the identification of the CR particles will allow to discriminate some of the proposed theories. For a recent review on UHECRs see (Nagano and Watson, 2000). The Auger Experiment (Auger Collaboration, 1997) aims to measure UHECRs with two detectors of 3000 km^2 each, positioned on the southern and northern hemisphere. However, only the secondaries are measured which the CR particles produce in the atmosphere. Particle detection at ground level is complemented with measurement of fluorescence light emitted in air. Arrival direction, energy, and identity of the primary particle have to be reconstructed from the air shower observables. For this purpose numerical models are employed that predict observable quantities as a function of the properties of the primary particle. Those models rely on experimental knowledge on hadronic and electromagnetic interactions, particle transport and decay and on theoretical ideas to extrapolate into kinematical and energy regimes not accessible in the lab. Analysis and interpretation of air shower data, therefore, always depends on the model used, and the larger the extrapolation from firm knowledge the bigger uncertainties become. Two models used within the Auger Collaboration are AIRES (Sciutto, 1999) and CORSIKA (Heck, 1998). In this paper we attempt a model comparison with emphasis on those quantities that will be measured by the Auger experiment and on which Auger physics results will likely rest.

2 The Programs

AIRES and CORSIKA provide both fully 4-dimensional Monte Carlo simulations of proton, photon, and nucleus-induced air shower development in the atmosphere. Both simulate hadronic and electromagnetic interactions, propagate particles through the atmosphere, account for the Earth's magnetic field, for decays, energy loss and deflection (and many less important processes), and produce eventually a list of all particles reaching ground level.

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AIRES is originally based on MOCCA (Hillas, 1997), but was significantly improved and extended. It uses its own set of routines for electromagnetic interactions (of $e^{\pm}$ and γ), decays and propagation. The additions comprise a link to the external high energy hadronic interaction models SIBYLL or QGSJET, muon pair production and bremsstrahlung, photonuclear reactions, the Landau-Pomerantchuk-Migdal (LPM) effect of high-energy γ and $e^{\pm}$, and the simulation of exotic primaries, (e.g. ν), (Bertou et al., 2001).

CORSIKA developed over the last 12 years to a standard analysis tool of the air shower community. CORSIKA attempts to model the individual processes of the shower development in as great detail as possible, to some extent irrespective of the computing effort needed. It employs proven solutions wherever available. So a variety of hadronic models have been linked to CORSIKA and are used and updated to the specifications of their respective authors. EGS4 (Nelson et al., 1985) is used for simulation of electromagnetic interactions, all two and three-body decays, with branching ratios down to 1%, are modelled kinematically correct and particle tracking and multiple scattering are done in great detail, even for strange and charmed particles. Also CORSIKA contains photonuclear reactions, muon pair production and bremsstrahlung, and the LPM effect.

Both programs use a statistical thinning algorithm (Hillas, 1981) to keep computing times and particle output at a manageable level. Particles are followed individually down to a chosen fraction of the primary energy, from then on only a subset of particles from each interaction is followed, while others are discarded. The particles followed acquire an appropriate weight to account for the energy of those discarded.

3 The Hadronic Models

The major source of uncertainty in air shower analysis stems from the hadronic interaction models. Soft hadronic interactions, i.e. those with low momentum transfer, are not calculable from first principles, and those are the interactions that are most important for the air shower development. The models, therefore, are always partially phenomenological. At present, high-energy interaction models based on Gribov-Regge theory (GRT) of multi-Pomeron exchange are favoured. They describe collider results rather well and provide a theoretical framework for extrapolation to higher energies. Many models are updated and new and more elaborate ones are formulated. At present, however, only two models reach up to 10^{20} eV. For a first test see, e.g., Heck et al. (2001). The model that seems to describe a variety of experimental findings from $10^{12} - 10^{16}$ eV best is QGSJET (Kalmykov et al., 1997). For this comparison both, AIRES and CORSIKA, use QGSJET for high energy interactions. However, at energies below ≈ 100 GeV the high-energy models start to get problems, since particle production is constrained by the small amount of energy available. At energies ≤ 10 GeV many measurements on hadron production exist. Cross-sections, multiplicities and particle fractions have been measured for many projectiles and targets. Still there is no detailed theory to model this from first principles, but phenomenological descriptions are fairly detailed. The low-energy model is of great importance, since all signals measured in an EAS experiment are produced by low-energy particles that come from low-energy interactions. Especially particle ratios and energies can be altered by those interactions.

AIRES uses an extension of the Hillas Splitting Algorithm (HSA) (Hillas, 1981) in which the initial energy is split at random into smaller and smaller portions. There are only two free parameters, one regulates the energy fraction at which the splitting occurs (usually uniformly distributed) and one determines the number N of subsequent splittings that are applied. Finally the energy portions are attributed to pions and nucleons. The HSA can be easily configured to approximately emulate the multiplicities and energy distributions of other models. However, cross-sections, transverse momenta distributions and composition of secondaries need to be inserted from outside. While the electromagnetic part of the shower seems to be rather insensitive to the setting of HSA parameters, the number of muons with $E_\mu < 10$ GeV varies by up to 40%.

CORSIKA uses GHEISHA (Fesefeldt, 1985), which was developed for detector simulations at collider experiments and is also used for hadronic interactions within GEANT. GHEISHA was tuned to experimental results over a variety of projectiles and targets in the few-GeV region and, consequently, reproduces cross-sections and particle production rather well. Although problems relating to energy and momentum conservation have been reported, GHEISHA is still a good choice to simulate the low energy portion of hadronic showers.

To cover the energies between the few-GeV range and the region where GRT models work comfortably, models on both sides have to be stretched to their limits. As a compromise, in both CORSIKA and AIRES, the low energy models are used below 80 GeV and the high energy model above. While in CORSIKA the transition between the two models shows a discontinuity at 80 GeV, the HSA in AIRES was tuned to reproduce a multiplicity as averaged over QGSJET and GHEISHA for $E < 80$ GeV. Hence, multiplicities are higher in AIRES by up to $\approx 30\%$ as compared to CORSIKA.

4 Comparison and Results

The Auger experiment has two major observables: the longitudinal shower development as measured by the fluorescence light detectors, and the lateral energy density of ground particles as measured by the array of water-Cerenkov detectors. Therefore, the longitudinal shower development, and the ground particle distributions have been analysed. To perform a comparison between AIRES and CORSIKA, with each program 100 vertical proton-induced showers of 2×10^{19} eV have been simulated with thinning at a level of 10^{-7} E_0. Since both programs use the same hadronic interaction model for high energies, this comparison tests only differences due to the low energy hadronic interaction model, the electromagnetic part and the particle propagation.

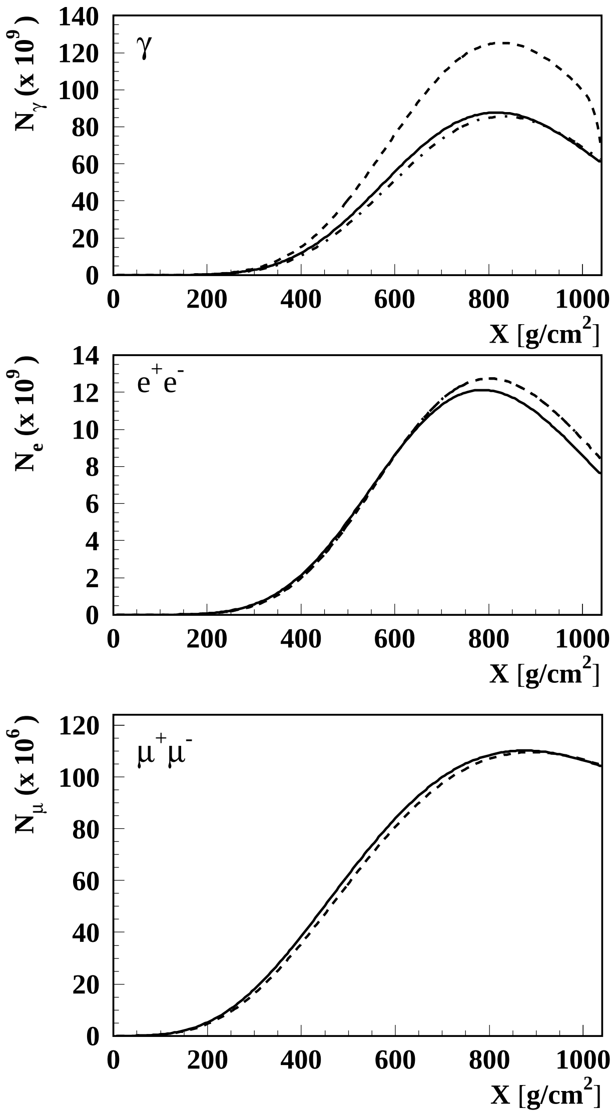

Fig. 1. Longitudinal development of N_γ, $N_{e^\pm}$ and $N_{\mu^\pm}$ with atmospheric depth. CORSIKA: solid line, AIRES including (excluding) upward going particles: dashed (dot-dashed) line

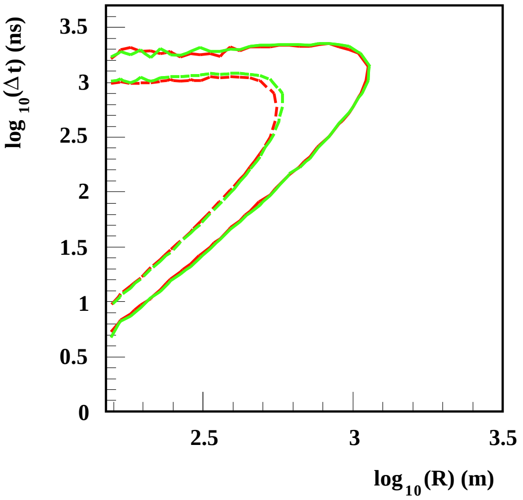

Fig. 2. Particle density contours for photons as function of core distance and arrival time. CORSIKA: black, AIRES: grey.

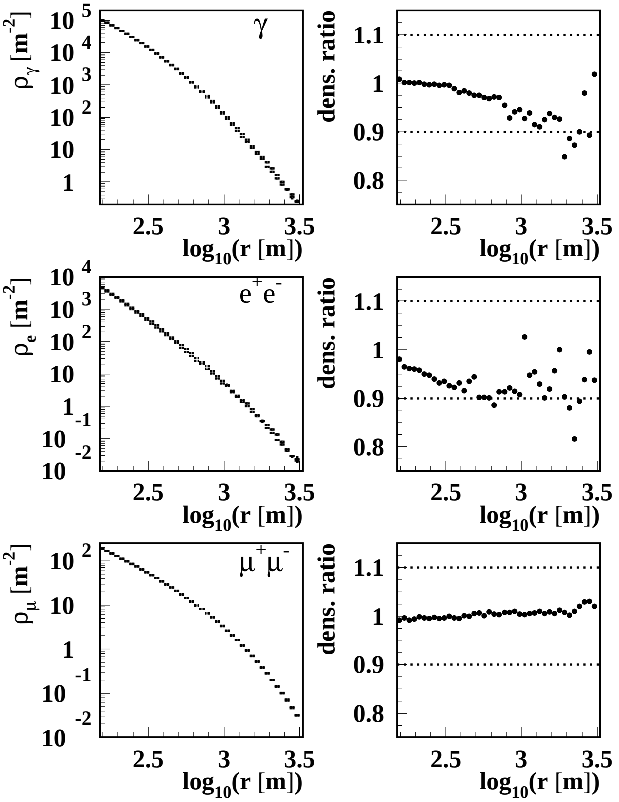

Fig. 3. Lateral particle densities for photons, electrons and muons. Left: particle densities. Right: relative difference between AIRES and CORSIKA as function of core distance.

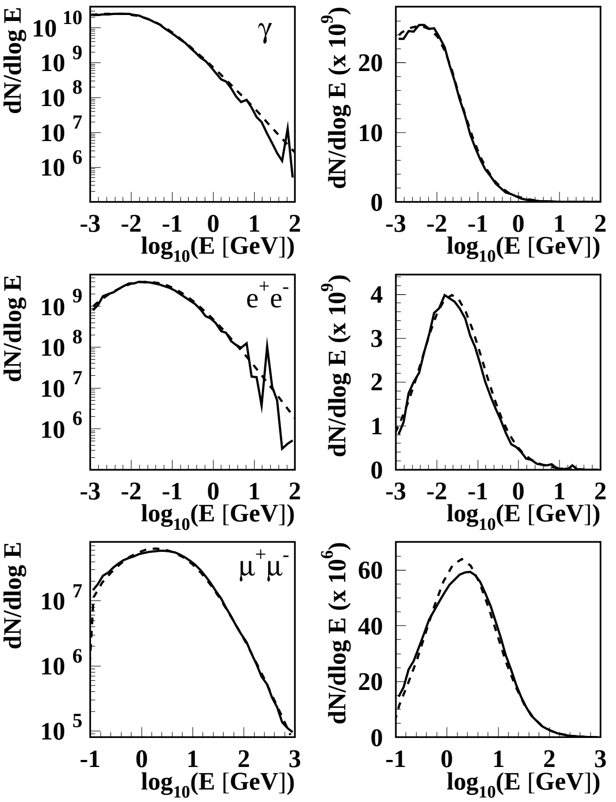

Fig. 4. Energy distributions for photons, electrons and muons. Left: logarithmic abscissa, Right: linear abscissa. CORSIKA: solid line, AIRES: dashed line.

Longitudinal shower development. The fluorescence light yield is determined by the energy deposit in the atmosphere, which, in turn, is dominated by the ionization due the numerous charged particles close to the shower axis. Thus, it relates well to the total number of electrons (and positrons) as a function of depth. This curve, however, is dominated by the high energy model and how it transfers the initial hadronic energy into the electromagnetic channel. The longitudinal shower development is crucially dependent on the inelastic cross-section and the inelasticity of interactions. Thus, low energy hadronic and electromagnetic models impose only second order effects on it. The evolution of $N_{e^+e^-}$ as a function of atmospheric depth agrees well between the two models, the electron numbers at the maximum of the shower development differ by less than 6% (see Fig. 1). The muon number as function of depth, which sensitively depends on details of the hadronic models, agrees even better. The differences at the shower maximum about 3%. There is a large difference apparent in N_γ as function of depth This is due to the fact, that in CORSIKA upward going particles are discarded. Those are predominantly very low energy (sub MeV) photons which contribute less than 2% to the energy deposit in the atmosphere. The disagreement in N_γ vanishes almost completely if AIRES discards the upward going particles (dot-dashed line). At ground level where no upward going particles exist the photon number agrees to about 10%.

Lateral distributions. The Auger array detectors measure the Cerenkov yield of shower particles in water. The array detectors are positioned on a hexagonal grid with 1.5 km distance. This means that rarely detectors will be close to the shower core. Typically, Cerenkov densities will be recorded in the range $r > 300$ m and this is what is checked by simulations. Fig. 3 shows the lateral densities of secondary photons, electrons and muons. The agreement is very good. The density ratios, 2(A-C)/(A+C), on the right emphasise the differences. With core distance CORSIKA tends to predict slightly higher densities, reaching $\approx 10\%$ at km distances. The muon densities agree even better. Only at $r \approx 3$ km a deviation of about 3% is observed. Fig. 2 shows the photon distribution as function of core distance and arrival time. As expected, the larger the core distance the later the particles arrive on average. The agreement between AIRES and CORSIKA is excellent. The good agreement between the models, despite the differences on the microscopic level, demonstrates that particle densities at large core distances are mainly determined by $p_\perp$ at particle production and by multiple scattering, and less by details of the low energy models.

Energy distributions. The Cerenkov density in a water tank depends not only on the particle density but also on the energy the particles carry. Electrons and photons are basically absorbed in the water, i.e. deposit all their energy (typically 1-10 MeV), while muons usually penetrate the tank and release an energy of $\approx$ 2 MeV/cm $\times$ their tracklength (typically 240 MeV). Together with the fact that the muon density decreases slower with r than the electron and photon densities, this means that the muon component is dominant at large distances. Also the energy distribution has a more direct relation to the low energy hadronic model than longitudinal or lateral distributions, since the form of the shower is basically determined from the higher energy interactions. Fig. 4 shows the energy distributions for photons, electrons and muons in a linear and a logarithmic display. The general agreement between AIRES and CORSIKA distributions is quite good. The most obvious discrepancies (in AIRES with respect to CORSIKA) are a slight excess of photons and electrons with $E > 10$ GeV, and a deformation of the muon spectrum below 3 GeV, leading to a deficit for muons with $E < 0.5$ GeV and an excess for $0.5 < E < 3$ GeV. Rather likely both discrepancies stem from the low-energy hadronic model, e.g from the higher π yield in the HSA as compared to GHEISHA.

Runtime performance. The comparison showed that AIRES is about 3.5× faster than CORISKA. For simulations of highest energy showers with minimum thinning, computing time may be the limiting factor and this difference in speed may prove important. Also the particle output of AIRES is smaller than that of CORSIKA. Both programs store 8 words of output information per particle (i.e. particle id, p_x, p_y,p_z, x, y, t, weight). CORSIKA stores each word with 32 bits (4 bytes), while AIRES provides the output in its own compressed format with about 18 bits/word. Also this may be of advantage in case a large shower library is produced and the available disk space is limited.

5 Conclusion

The general agreement between AIRES and CORSIKA in longitudinal, lateral and energy distributions is very good. No discrepancies are found that are beyond the 10% level. The overall systematic uncertainty in EAS simulations is dominated by the high energy hadronic interaction models, which were not tested in this analysis. The main advantage of AIRES over CORSIKA is that it is faster and produces a smaller output. CORSIKA, however, offers a larger variety of elaborate models from specialist authors and, therefore does not need adjustment of model parameters.

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