Proceedings of ICRC 2001: 494

ICRC 2001

Comparisons of CORSIKA-generated Showers with HiRes Data

A. Zech, for the HiRes Collaboration

Rutgers University, Piscataway, NJ 08855

Abstract. We have generated UHE cosmic ray showers using the CORSIKA program and the QGSJet hadronic interaction code, and have simulated the response of the HiRes detector to the showers. We included in the simulation the triggering and DAQ characteristics of the detector and the background sky noise. We processed these Monte Carlo events with the same analysis program run on HiRes data.

To efficiently use the CORSIKA events, we developed a library of showers generated at various discrete energies and zenith angles. Since the showers fit very well to the Gaisser-Hillas formula, we characterized each shower in the library by its Gaisser-Hillas parameters. Then in the detector-simulation program we placed the showers at different distances and azimuthal orientations, and scaled the Gaisser-Hillas parameters in energy and zenith angle to reproduce continuous energy and zenith angle distributions.

We present a detailed set of comparisons between the Monte Carlo simulations and actual HiRes data.

1 Introduction

In the study of ultra high energy cosmic rays (UHECR) a crucial role is played by Monte Carlo programs. There are two types of these programs, those which simulate the development of showers in the atmosphere, and those which simulate the response of detectors to those showers. Measurements of cosmic rays' energies and compositions depend on these Monte Carlo simulations because shower-sampling programs like AIRES (Sciutto, 1998) and CORSIKA (Heck et al., 1998) are our primary standard against which data is compared to determine the properties of cosmic rays seen in experimental data. The second type of Monte Carlo programs, which take these showers and simulate the response of detectors, play the crucial roles of demonstrating our understanding of how our detectors perform, determining our experimental resolution, and calculating the acceptance of our experiment.

Correspondence to: aszech@physics.rutgers.edu

In the High Resolution Fly's Eye Experiment (HiRes) we use CORSIKA (with the QGSJet hadronic simulation package (Kalmykov et al., 1997)) to generate UHECR showers in the atmosphere. For an atmospheric fluorescence detector such as ours the important parameter to simulate is the number of charged particles in the shower as a function of slant depth. We have found that for individual CORSIKA showers this parameter is very well fit by the Gaisser-Hillas function.

Our detector-simulation Monte Carlo program begins with Gaisser-Hillas fits to CORSIKA showers and calculates the amount of fluorescence light emitted by the charged particles in the showers, the number of photons collected by our mirrors and number of photoelectrons seen by our phototubes, and the operation of our experiment's trigger and data acquisition system. Simulated events are saved in the same format as the data. The same analysis program is run on both data and on Monte Carlo events to make comparisons between the two distributions.

In order for these comparisons to provide statistically significant results, we need to generate a considerable number of Monte Carlo events. The running times of the shower-sampling and the detector-simulation programs are therefore of high importance. The time it takes to generate air showers depends strongly on the energy of the primary particle and on the precision that is needed in the longitudinal development of the number of charged particles. We use the statistical thinning algorithm provided by CORSIKA to reduce the number of low energy particles that have to be processed individually only if the energy of a secondary particle falls below 10^{-5} times the energy of the primary particle. At higher energies each single particle is processed in the simulation. This accuracy leads, together with an E^{-3} energy spectrum for primary energies between $3 \cdot 10^{16} eV$ and $3 \cdot 10^{20} eV$, to a running time of approximately 15 minutes on the average for the generation of one air shower on one of our 440MHz DEC ALPHA workstations. Simulating the detector response for a given parameterized shower, on the other hand, takes less than one second of running time.

2 The Shower Library

Since the generation of showers using CORSIKA consumes much more computer time per event than the simulation of the detector response, we decided to build a library of CORSIKA showers and reuse them repeatedly.

We characterize each shower by seven parameters: the atmospheric depth of first interaction, the energy of the primary particle, the zenith angle of the shower axis and the four fit parameters that describe the longitudinal development of the shower in the Gaisser-Hillas function (Gaisser and Hillas, 1977):

$$N(X) = N_{max} \cdot \left(\frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max} - X_0}{\lambda}} \cdot e^{\frac{X_{max} - X}{\lambda}}$$

This function describes the number of charged particles at a given atmospheric depth X. N_{max} is the value at the maximal size of the air shower, X_{max} the depth where this maximum occurs. X_0 and λ determine the shape of the shower development. We fit this function to the longitudinal distribution of charged particles that we generate with CORSIKA in steps of 5 g/cm^2 vertical depth.

Our shower library consists currently of three times five files containing information of 200 showers each. We have generated events at five fixed energies from $10^{16} eV$ to $10^{20} eV$ in logarithmic steps and at three fixed zenith angles from 0° to 48° in steps with equal differences in solid angle. Up to now, only showers with proton primaries have been included in our library, but we will expand it to contain showers caused by iron particles in the near future. Since we want to generate Monte Carlo events with a continuous energy and zenith angle distribution, we have studied the dependence of the Gaisser-Hillas parameters on these quantities. We have found that N_{max} varies linearly with the energy of the primary particle and that X_{max} is linear in the logarithm of this energy. The width of the distribution of N_{max} decreases with energy. Both N_{max} and X_{max} do not vary significantly with the zenith angle. λ shows only little variation with energy and zenith angle, whereas X_0 shows a linear dependence on the logarithm of the energy at certain ranges of zenith angles. However, fluctuations of this last parameter at a given energy and angle for different showers are large. The depth of first interaction varies only slowly with energy and angle. We decided to use the dependences of N_{max},X_{max} and X_0 on the energy of the primary particle to scale these parameters to energies between the fixed values of the gridpoints of our library.

When the detector-simulation program generates an event, it first chooses the azimuthal angle of the shower axis, the distance of the detector from the shower axis and the angle of the shower detector plane around the axis at random. The zenith angle is taken from a uniform solid angle distribution and the energy of the primary particle from the spectrum measured by the "Fly's Eye" experiment (Bird et al., 1993). The program then reads one shower from the file at the gridpoint of our library that is closest to the chosen energy and zenith angle. The N_{max} of this shower is scaled linearly to the energy, its X_{max} and X_0 are scaled logarithmically, λ and the depth of first interaction are taken over directly by the detector-simulation program. A shower is now reconstructed with these parameters and the detector response is being calculated. Each trial event takes about one second to generate. This allows us to generate enough Monte Carlo events for comparison with one month's data in a few hours.

An important aspect of our method of generating Monte Carlo events is that by using information about individual CORSIKA showers in the detector-simulation, rather than dealing with mean values of shower distributions, we maintain the natural fluctuations of particle number and shower geometry.

3 Tuning the Monte Carlo Program

In order to generate Monte Carlo events that best resemble the data we tuned the generated energy spectrum and adjusted a variety of conditions to follow the day-to-day variations in the running of the experiment. These conditions included trigger levels, background sky noise, and atmospheric conditions.

We apply in our detector-simulation program the same triggers that exist in the hardware of the "HiRes-2" detector. In a primary trigger, sums of pulse amplitudes are determined for every row and every column of each cluster of photomultiplier tubes. If the trigger sums of a cluster that are above a given trigger-threshold show a required pattern, all tubes of this cluster are scanned individually for pulse amplitudes above a certain threshold (confirming scan). If a cluster is found to have a required number of tubes with signals above threshold, all tubes of this cluster are scanned again with a lower threshold and read out in a datafile (readout scan). By comparisons between data and Monte Carlo events we have seen that the distribution of photoelectrons per track-length and the reconstructed energy spectrum are sensitive to changes in the trigger gains, that are made at times in the detector electronics. This has led us to build a database containing these trigger gains, the varying thresholds of the confirming and readout scans, as well as variations of other quantities of interest. When simulating Monte Carlo events for comparison with real data of a certain range of days, we use the values from the database corresponding to this time range in the detector simulation to generate events under the same conditions as the data we want to compare them to.

This database has been expanded to include information about background sky noise on a day-by-day basis. Data-Monte Carlo comparisons showed us that we have to add a significant fraction of randomly distributed noise hits in the simulation to the signals from photons that arrive from a shower in the photomultiplier tubes. These sky noise hits, in addition to the Poisson distributed noise of the electronics simulation, are necessary to generate realistic Monte Carlo events. The sky noise is taken directly from observational data and stored in our database to be read by the detector-

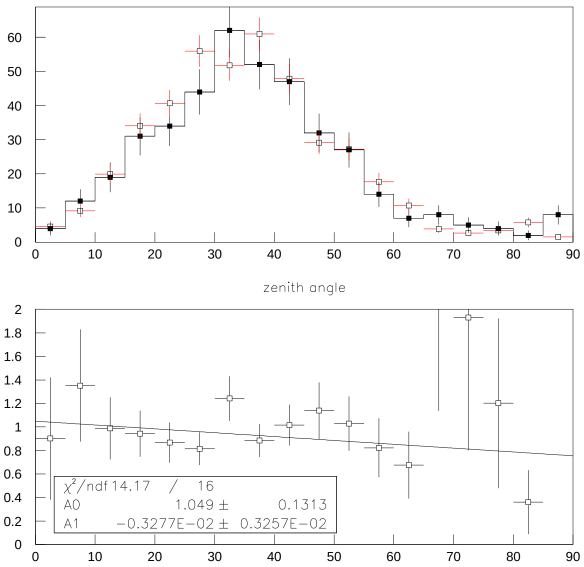

Fig. 1. top: zenith angle distribution (data - filled squares; Monte Carlo - open squares)
bottom: ratio of data divided by Monte Carlo

simulation program.

Of high importance for the energy reconstruction of events is also a realistic treatment of atmospheric conditions by the Monte Carlo program. We therefore include a description of the atmosphere, parameterized by the aerosol attenuation length and scale height, in our database on an hour-by-hour basis. This information has been derived from analysis of laser shots that we perform regularly during data collection.

4 Comparisons between Data and Monte Carlo

To judge the accuracy of our Monte Carlo simulation of the HiRes data we plot various quantities for the data and superimpose Monte Carlo histograms of the same quantities. We adjust the area under the Monte Carlo histograms to be the same as that of the data. Histograms of three types of variables will be presented at the conference: that of geometric quantities, variables indicative of apparatus performance, and UHECR kinematic variables.

In this paper, we show two plots of interest: the zenith angle distribution of showers, and the distance from the detector to the shower mean.

Figure 1 (top panel) shows the zenith angle distribution of air showers observed by the "HiRes-2"- detector in December 1999 and January 2000 (filled squares). 427 real events are compared to 1134 Monte Carlo generated events (open squares). The zenith angle of each event—real or Monte Carlo—is reconstructed with the same analysis program from the timing and pulse height information of the triggered photomultiplier tubes. In the lower panel of figure 1 we show the ratio of the data distribution divided by the Monte Carlo distribution. A linear fit of this plot yields a slope that is unity within one standard deviation, confirming that the zenith angle distributions of real data and Monte Carlo events agree very closely.

Another basic parameter that can be studied to compare the geometry of real and computer-generated showers is the distance of the detector from the shower mean. We determine the shower mean by weighing each photomultiplier tube along the reconstructed shower track by the number of photoelectrons recorded by that tube. We use again the same reconstruction program to calculate the distance of the detector from this shower mean for both data and Monte Carlo events. The distributions shown in figure 2 (top panel) have a rising part up to a distance of about 4 km, since the number of detected showers increases with the area, i.e. with the square of the distance. At larger distances the decrease in number of events that are bright enough to be detected dominates the behavior of the graphs. The distribution of 378 events detected by "HiRes-2" (filled squares) is in good agreement with the 1041 Monte Carlo events (open squares). The bottom panel shows again the ratio of data divided by Monte Carlo. Again the slope of the linear fit to the ratio is within one standard deviation of unity.

5 Conclusions

We have described a novel way of generating large numbers of Monte Carlo events using a library of CORSIKA showers.

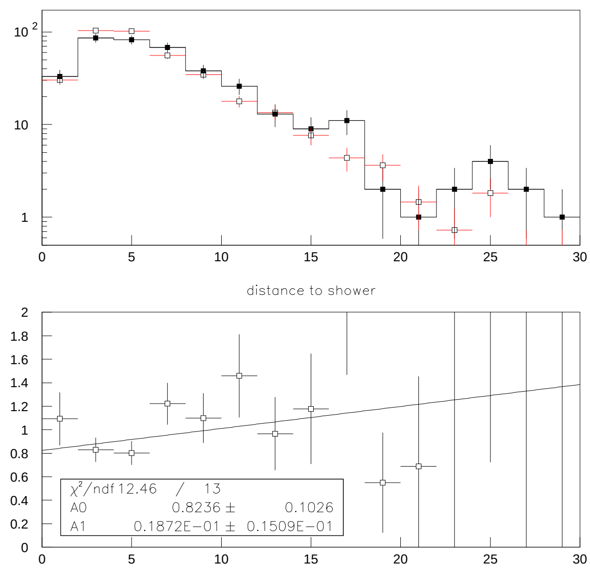

Fig. 2. top: logarithm of distance of the detector from the shower mean (data - filled squares ; Monte Carlo - open squares)
bottom: ratio of data divided by Monte Carlo

The Monte Carlo program has been tuned by including characteristics of the data such as trigger levels and sky noise.The resulting events resemble the data very closely.

The close agreement between the Monte Carlo simulation and the data give us confidence that we understand our detector and that our Monte Carlo program correctly calculates the acceptance of the detector.

Acknowledgements. This work is supported by US NSF grants PHY 9322298, PHY 9974537, PHY 9904048, PHY 0071069 and by the DOE grant FG03-92ER40732 and by the Australian Research Council. We gratefully acknowledge the contributions from the technical staffs of our home institutions. The cooperation of Colonel Fisher, US Army and Dugway Proving Ground staff is appreciated.

References

Sciutto, S. J., "AIRES: A System for Air Shower Simulations." Auger technical note GAP-98-032 (1998); http://www-td-auger.fnal.gov:82

Heck, D., Knapp, J., Capdevielle, J. N., Schatz, G., Thouw, T., Report FZKA 6019 (1998), Forschungszentrum Karlsruhe; http://www-ik3.fzk.de/heck/corsika/physics_description/corsika_phys.html

Kalmykov, N. N., Ostapchenko, S. S., Pavlov, A. I. *Nucl. Phys. B (Proc. Suppl.)* 52B (1997) 17

Gaisser, T. K. and Hillas, A. M., Proc. 15th Int. Cosmic Ray Conf. (Plovdid), 8 (1977) 353

Bird, D. J. et al., *Phys. Rev. Letters* 71 (1993) 3401