

## A Comparison between Hadronic Interaction Models and Observations by the Telescope Array

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**Abstract:** The observation of ultra-high energy cosmic rays presents the opportunity to study particle interactions orders of magnitude more energetic than can be attained in particle colliders. However, the events are rare and only their extensive air showers can be studied experimentally. Monte Carlo shower simulation programs use interaction models which extrapolate cross sections from accelerator experiments and attempt to predict how experimental shower data should appear. The models make two sets of observable predictions. The first set predicts the longitudinal development of cosmic ray air showers, which can be tested by an air fluorescence detector. The second set of predictions pertain to the lateral distribution of secondary particles at the ground which can be measured by an array of particle detectors. Comprehensive comparisons will be shown between showers observed by the Telescope Array and simulated showers utilizing the QGSJET, SYBIL, and EPOS hadronic interaction models. Particular attention will be paid to energy scale differences between air fluorescence and ground array observations, lateral particle distribution at the ground, and specific shower observables such as the distributions of primary zenith angles, number of counters per shower, and counter signal strengths.

**Keywords:** extensive air shower, simulation, comparison.

### 1 Introduction

The Telescope Array (TA) is the largest experiment studying ultrahigh energy cosmic rays in the northern hemisphere. It is located in Millard County, Utah, and consists of a surface detector (SD) of 507 scintillation counters, each of area  $3\text{m}^2$ , deployed in a grid of 1.2 km spacing, plus a set of 38 fluorescence telescopes located at three sites around the SD looking inward over the array. Both detector systems of TA started collecting data in 2008.

An important experimental technique used in the cosmic ray energy spectrum measurement is the calculation, using the Monte Carlo simulation method, of the efficiency with which the detector observes cosmic ray induced extensive air showers. Prior to the TA experiment, high-fidelity Monte Carlo (MC) simulations have been available for fluorescence detectors (FDs), which measure the fluorescence light emitted by nitrogen molecules excited by the passage of shower particles in their vicinity. Accurate simulations for the other major detector type, surface scintillation arrays, have only recently become possible with the rapid growth of computational and storage capacity over the past decade, coupled with the maturity of sophisticated and realistic shower generation codes over the same time frame. In particular, the difficulty of generating accurate Monte Carlo simulations of air showers has limited the surface array technique to the energy regime where the detector is 100% efficient [1]; i.e., only at the high energy end of the detector's sensitive range.

In order to simulate accurately the ground-level particle densities measured by surface detectors, along with their fluctuations, a shower generator code needs in principle to track every particle created in the avalanche process down to below its critical energy. In practice, available CPU power and storage space limit one to generating only a small number of shower particles, insufficient for an accurate calculation of detector acceptance, or for a useful

comparison of data and MC distributions. An approximation technique called "thinning" typically is used in programs like CORSIKA [2] and AIRES [3] to reduce CPU time requirements. Under the thinning approximation, nearly all particles with energies below a preselected threshold (orders of magnitude higher than the critical energy) are removed from the shower. Only a few representative particles are kept with weights to account for those, in the same region of phase space, that have been "thinned" out.

The thinning method usually gives an adequate description of particle distributions in the core region of a shower where enormous numbers of particles are found (and where essentially all of the fluorescence light is generated). For surface detectors, which sample the particle density at ground level, the enormous flux saturates any counter in proximity to the shower core. Typically, useful sampling is based on detectors at the scale of the detector spacing or more. For experiments, like TA, that are optimized to measure the highest energy cosmic rays, this distance scale is of the order of a kilometer. While a thinned shower is able to reproduce the average particle densities reasonably well on the kilometer scale from the shower core, the weighted particles cannot model the shower-to-shower fluctuations or even the fluctuations at different azimuthal angles around the shower core. The RMS deviations from the average densities in a thinned shower are typically off by an order of magnitude or more from that obtained from those seen in the few "unthinned" showers one can afford to generate. Thinning is therefore too crude of an approximation to give a faithful representation of even the simulated air shower itself, let alone real cosmic-ray induced showers. Some experiments have claimed to overcome this intrinsic difficulty by restricting their analysis to the highest energy range where the efficiency of the detector approaches unity. However, if quality cuts are used to select only a subset of the data, then the use of a simulation is still needed to calculate acceptance. In that case the use of thinning can

and probably does introduce significant systematic biases because the thinned Monte Carlo (MC) simulation cannot accurately reproduce the tails expected in the distribution of cut parameters. Quality cuts are invariably used to remove outliers in such tails.

In the simulation of air showers for calculating the acceptance of the Telescope Array experiment, we have developed a "de-thinning" procedure to compensate for the shortcomings of the thinning. Using the thinned CORSIKA output, we replace each representative particle of weight  $w$  with an ensemble of  $w$  particles propagated in a cone about the weighted particle. A detailed prescription of our de-thinning process was published in an earlier article [4]. In that article, careful comparisons were made between de-thinned and "un-thinned" (the latter referring to showers generated without any thinning), and excellent agreement was found in the statistical properties of the two sets of simulations. Our de-thinned sample overcame all of the essential shortcomings of the thinning approximation.

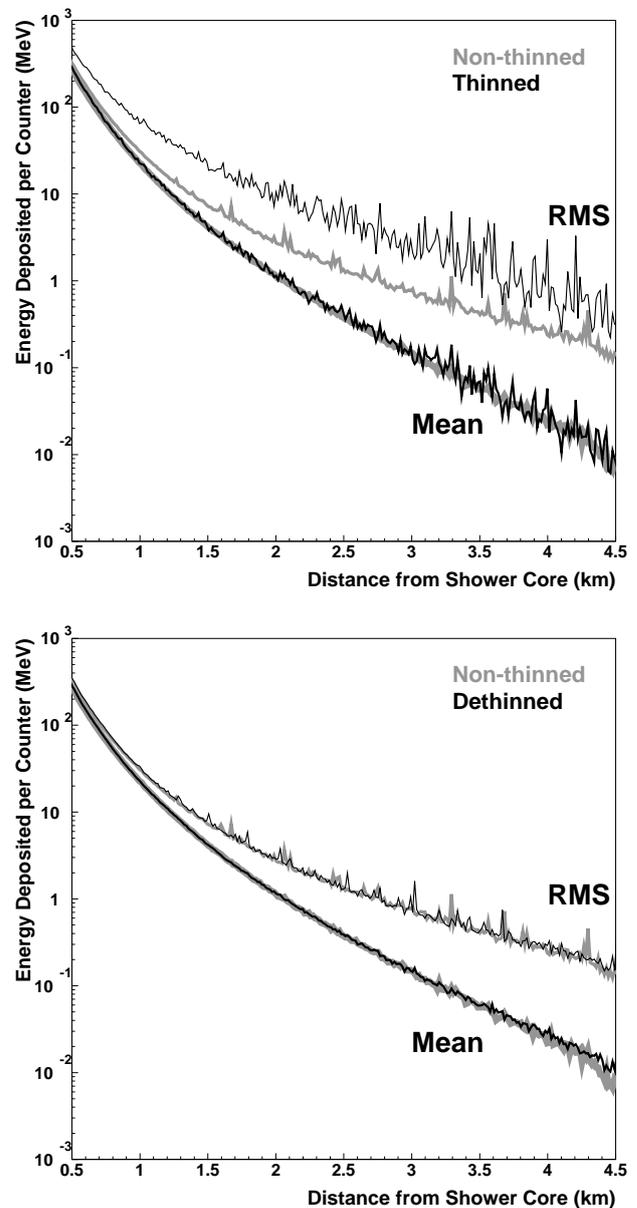
While this method was originally developed to improve the SD measurement of the cosmic ray energy spectrum, it also is a powerful tool for doing thorough comparisons of different hadronic models with actual observations. Specifically, we will apply our technique to iron and proton shower libraries for QGSJET, SYBILL, and EPOS.

## 2 Surface Detector Monte Carlo Simulation

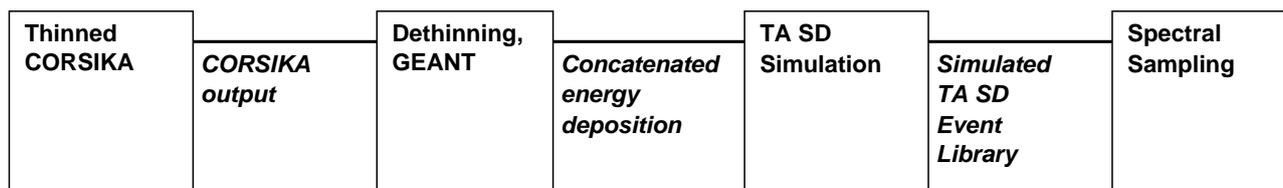
For our simulations, we utilized the CORSIKA 7.350 [2] simulation package. For each simulated event set, we selected the FLUKA2008.3c [5, 6] low energy hadronic model and the EGS4 [7] electromagnetic model. Separate iron and proton event sets were created for the following high energy hadronic models: QGSJET-II-04 [8], SIBYLL [9], and EPOS [10].

The first step in generating a comprehensive simulation of the TA SD data set is to create a library of thinned CORSIKA showers. This library consists of 9,800 extensive air showers with primary energies distributed in  $\Delta \log_{10} E = 0.1$  bins between  $10^{17.35}$  eV and  $10^{20.55}$  eV. The number of showers in each bin ranges from 1000 in the lowest energy bin to 250 in the highest energy bin. These showers are simulated with zenith angles from  $0^\circ$  to  $60^\circ$  assuming an isotropic distribution. It is important to note that in our final analysis we only include events with  $E > 10^{18.0}$  eV and  $\theta < 55^\circ$ . However, events must be simulated beyond these limits in energy and inclination in order to give a complete understanding of our detector acceptance as well as our energy and angular resolutions.

Each shower in the Corsika library is then subjected to de-thinning [4]. For each simulated event, all shower particles that strike the ground are divided spatially by their landing spots into  $6 \times 6 \text{ m}^2$  "tiles" on the desert floor and into 20ns wide bins by their arrival time. The total energy deposited by all particles that landed in a particular tile, and into a virtual TA SD counter located at its center, is calculated using the GEANT4 simulation package [11]. Note this analysis assumes many more virtual SD counters (spaced every 6 m instead of 1.2 km) than are actually present in the experiment. Back scattering of particles striking the ground within the tile is included in the simulation. The energy deposited as a function of time is stored in the shower library. Figure 1 shows the comparison of energy deposition in SD counters vs. distance-to-core from a simulated  $10^{19}$  eV shower before and after de-thinning. The plot at the bottom,



**Fig. 1:** A comparison of energy deposition per counter versus perpendicular distance-to-core for a non-thinned and a thinned simulation before (top) and after (bottom) the de-thinning procedure is applied. Both simulations are of a proton with a primary energy of  $10^{19}$  eV and a primary zenith angle of  $45^\circ$ . While the mean energy deposition agrees in all cases, the variation in the energy deposition (RMS) shows much better agreement after de-thinning.



**Fig. 2:** Steps for simulating the TA SD data set. Each box represents one or more computational routines used to produce the input files required for the next step.

made using a de-thinned shower, shows excellent agreement to an identical unthinned shower in both the mean energy deposit and its RMS variation, plotted as functions of distance-to-core. In contrast, the same plot on top comparing the same shower after thinning to the same unthinned shower shows a discrepancy in the RMS variation in energy deposition by up to an order of magnitude.

In the concluding step of the shower library generation, each tiled shower is resampled 2000 times through a detailed simulation of the detector, including electronics. The shower core positions, the azimuth of the shower axis, and event times are varied in this process. The detector simulation utilizes real-time calibration information from the TA SD to effect a highly detailed, time-specific simulation of the detector operating conditions. Additionally, random background particles are inserted into the electronics readout based on secondary flux derived from additional CORSIKA simulations of the low-energy cosmic ray spectrum reported by the BESS Collaboration [12]. The net result of this step is to convert each dethinned Corsika shower into a collection of simulated detector events in a data format identical to that produced by the TA SD instrumentation.

In order to achieve a highly accurate representation of the actual TA SD data set, we generated cosmic rays with a primary energy distribution and composition according to published HiRes energy spectrum [13] and composition [14], respectively. The resulting MC event set is then processed by the same analysis program as the TA SD data. This process chain is illustrated by the diagram in Figure 2.

### 3 TA Data/Monte Carlo Comparisons

In the oral presentation, numerous comparisons will be shown between simulated and real data sets. We will demonstrate that while some hadronic models and particle types are more consistent with the real data than others, none of the models are completely consistent with our observations.

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