30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

Comparison of hybrid and pure Monte Carlo shower generators on an event by event basis

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Abstract: SENECA is a hybrid air shower simulation written by H. Drescher that utilizes both Monte Carlo simulation and cascade equations. By using the cascade equations only in the high energy portion of the shower, where the shower is inherently one-dimensional, SENECA is able to utilize the advantages in speed from the cascade equations yet still produce complete, three dimensional particle distributions at ground level which capture the shower to shower variations coming from the early interactions. We present a comparison, on an event by event basis, of SENECA and CORSIKA, a well trusted MC simulation code. By using the same first interaction in both SENECA and CORSIKA, the effect of the cascade equations can be studied within a single shower, rather than averaged over many showers. Our study shows that for showers produced in this manner, SENECA agrees with CORSIKA to a very high accuracy with respect to densities, energies, and timing information for individual species of ground-level particles from both iron and proton primaries with energies between 1 EeV and 100 EeV. Used properly, SENECA produces ground particle distributions virtually indistinguishable from those of CORSIKA in a fraction of the time. For example, for a shower induced by a 10 EeV proton, SENECA is 10 times faster than CORSIKA, with comparable accuracy.

Introduction

SENECA is a hybrid air shower simulation, combining cascade equations with Monte Carlo (MC) to quickly produce fully descriptive ground particle distributions [1]. High energy cosmic ray experiments, such as the Pierre Auger Observatory, are dependent upon air shower simulations to understand shower development and detector response. Higher energy simulation has traditionally resulted in a significant computational problem. Thinning has been used to cut down computation times, but always at the cost of accuracy. Thinning introduces artificial fluctuations to the lateral distribution function (LDF).

By beginning with a high energy MC stage, using cascade equations in the one-dimensional regime of the shower, and MC elsewhere, one can reproduce the longitudinal profile [4] and the LDF [1] with a high degree of accuracy. For high energy showers, using a hybrid approach can reduce computation times by over a factor of ten [1] and allow for a superior thinning method.

Event by event method

CORSIKA has been well tested and is well trusted, and is therefore used as a standard to which SENECA can be compared. Previous studies have already shown that SENECA and CORSIKA agree well when comparing the average LDF of 10 EeV proton primary showers [1], as well as the average longitudinal profile for primary energies between 1 EeV and 100 EeV [4]. We will present a technique which allows for meaningful comparisons between SENECA and CORSIKA on an event by event basis.

A large contribution to the natural fluctuations of showers with identical primaries comes from the height and dynamics of the first interaction. By

ICRC 2007 Proceedings - Pre-Conference Edition

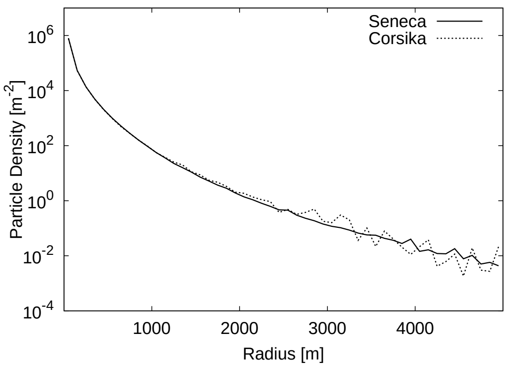

Figure 1: Total LDF for a vertical 10 EeV proton primary shower. Solid line represents SENECA, dashed line represents CORSIKA. The LDF was calculated by adding all the weight in 100 m wide rings.

using the same first interaction in both SENECA and CORSIKA, showers can be compared on an individual basis. This can be done by using the STACKIN option in CORSIKA [2]. The first interaction is simulated using SENECA, and secondary particles are written to a file which may be read in by CORSIKA. This was done for vertical proton showers of energy 1 EeV, 10 EeV, and 100 EeV at thinning levels of 10^{-6}, 10^{-7}, and 10^{-8}.

In order for this method to give meaningful results, it is crucial to use the same hadronic and electromagnetic models. In the hadronic case, QGSJet01 and Gheisha 2002 were used as the high energy and low energy models, respectively. If any discrepancies existed in the hadronic and muonic components, presumably arising from the use of cascade equations, our comparisons would reveal them.

Lateral Distribution Function

It was found that the results of our study are independent of the energy of the primary, so our discussion will focus on 10 EeV primary showers. By eye, the LDF for SENECA and CORSIKA are in agreement. Figure 1 shows the lateral density of particles for a single SENECA and CORSIKA shower. Discrepancies do not arise until a radius where fluctuations become large. In order to make a robust comparison, a library of 50 showers, all with the same first interaction, was generated, for both CORSIKA and SENECA, using a thinning level of 10^{-7}. The results of this comparison are shown in figure 2. Discrepancies in the averaged density of particles are less than 5% out to a radius of 3km, for both hadrons and muons, and the averaged LDFs are in agreement within one sigma at all radii.

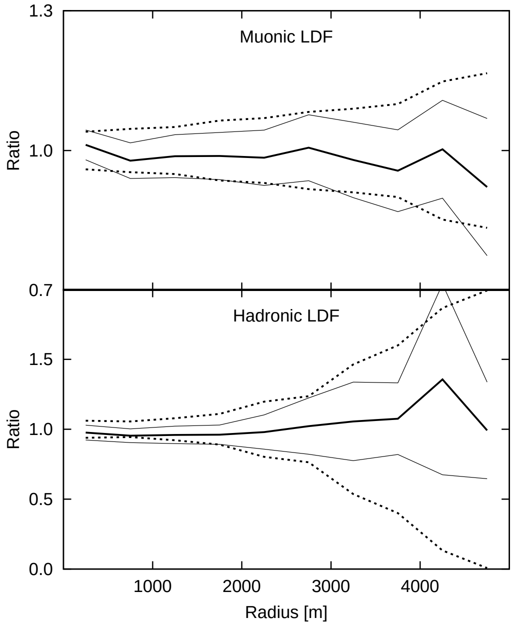

Figure 2: Ratio of SENECA LDF to CORSIKA LDF, for muons and hadrons. One-sigma bands are shown for CORSIKA by dashed lines, and for SENECA by the thinner solid lines. These errors include artificial and natural fluctuations. To create the LDFs that are compared, an average of 50 showers was used, all with the same first interaction.

Energy Distribution

A comparison of the energy distributions of electrons and muons can be seen in figure 3. Similar to what was found in the LDF comparison, the muonic energy distributions agree nicely. The average value of the distributions at both radii differ by at most 2%.

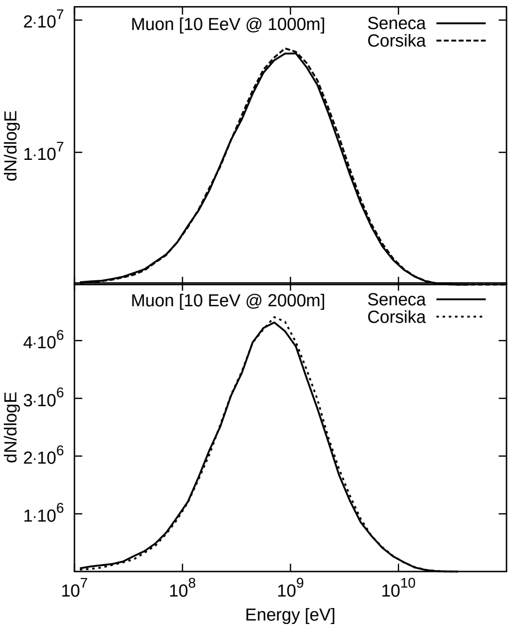

Figure 3: Energy distribution of muons, at a radius of 2000 m and 1000 m, of 50 10 EeV proton induced showers. The first interaction of all the showers is identical. The solid and dashed lines represent SENECA and CORSIKA, respectively.

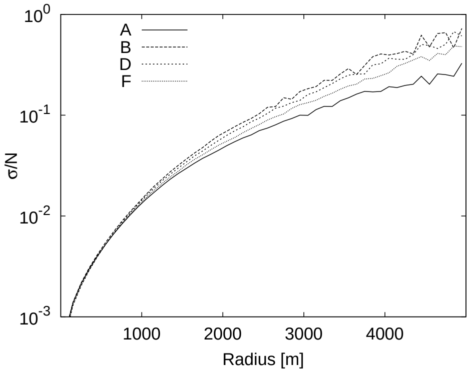

Figure 4: An estimate of artificial fluctuations for a variety of thinning methods (See Table 1), as explained in equation (1).

Thinning

The principle motivation for using cascade equations is the significant increase in speed. However, the thinning methods used by SENECA and CORSIKA are fundamentally different. In SENECA, the shower is followed exactly until the end of the cascade equations. Particles are sampled from source functions and assigned a weight that they will keep until the end of the simulation [1]. The nearest method available in CORSIKA is optimized thinning with maximum weight limits, in which Hillas or statistical thinning is effectively applied over an energy range specified by the parameters of the thinning [3].

A comparison of the artificial fluctuations induced by thinning is shown in figure 4. $\frac{\sigma}{N}$ is defined as

$$\frac{\sigma}{N} = \frac{\sqrt{\sum_i W_i^2}}{\sum_i W_i}, \tag{1}$$

where the sum is over all tracked particles and W_i is the weight of an individual particle. σ provides a measure of the artificial fluctuations induced by thinning. As can be seen, even when the maximum weights used are identical for CORSIKA and SENECA, SENECA produces less artificial fluctuations. This is because the cascade equations can be used to follow the shower exactly to quite low energies, below which there are so many particles that the fluctuations from thinning are small. In the example shown in figure 4, cascade equations were used down to 10^4 GeV and 10 GeV for the hadronic and EM portions, respectively. The SENECA shower has artificial fluctuations similar to a CORSIKA shower using thinning levels 10^{-6} and 10^{-9} for the hadronic and EM portions, respectively. The cascade equations naturally lend themselves to very efficient and effective thinning.

Efficiency

The relative efficiency of a thinning method and simulation, which takes into account speed and minimization of artificial fluctuations, can be defined as follows [3]

$$Q_A = \left(\frac{\sigma}{\sigma_A}\right)^2 \left(\frac{t}{t_A}\right) \tag{2}$$

Efficiency Comparison					
Label	Generator	Thinning Method	$W^{EM}_{(max)}$	$W^{Had}_{(max)}$	Q_A
A	SENECA	-	10,000	1,000	1
B	SENECA	-	10,000	10,000	3.2
C	SENECA	-	4,000	4,000	3.2
D	CORSIKA	Opt. 10^{-5}	10,000	10,000	8.7
E	CORSIKA	Opt. 10^{-6}	10,000	10,000	14.5
F	CORSIKA	Opt. 10^{-5}	1,000	10,000	7.3

Table 1: This table compares the efficiency of various thinning methods, in both SENECA and CORSIKA, to the efficiency of running SENECA with a hadronic weight of 1,000 and an electromagnetic weight of 10,000. Q_A is as defined in equation (2), where thinning method A has been used as the reference. So thinning A is 3.2 times more efficient than thinning B. Q_A for thinning method A is 1 by definition. In the case of SENECA, $W^{EM}_{(max)}$ refers to the final weight of electromagnetic particles, whereas for CORSIKA it refers to the maximum allowable weight, and likewise for $W^{Had}_{(max)}$.

where t is the computation times of the simulation, and σ is defined as the numerator of the right hand side of equation (1). σ_A and t_A correspond to thinning method A in table 1, which is used as a reference. For example, thinning method D has a Q_A value of 8.7, thus, thinning method A is 8.7 times more efficient than D. Table 1 compares a variety of thinning methods, in both SENECA and CORSIKA. Thinning method A was found to be the most efficient method for a 10 EeV shower.

Conclusion

The hybrid simulation method employed by SENECA has two very significant advantages over a pure MC simulation: speed and accuracy. SENECA is at least 7.3 times more efficient than CORSIKA, in terms of quickly producing showers with minimized artificial fluctuations. As has been demonstrated, this increase in efficiency comes at no cost in physical accuracy. SENECA is able to produce particle densities and particle energy distributions that are consistent to those produced by CORSIKA, when the models used in the simulation are fixed.

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