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# **3D Hybrid Air Shower Simulation in CORSIKA**

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Abstract: The interpretation of EAS measurements strongly depends on detailed air shower simulations. CORSIKA is one of the most commonly used air shower Monte Carlo programs. In the last two years many features were added to CORSIKA, including the option of hybrid simulation, a better access to the particles during shower development, and improved possibilities for users to access shower information. In this contribution we show how one can take advantage of the new options. Predictions for standard observables of the last release of CORSIKA 6.980 are shown.

Keywords: CORSIKA, CONEX, COAST, air-shower, simulation

# **1** Introduction

The experimental method of studying ultra-high energy cosmic rays is an indirect one. Typically, one investigates various characteristics of extensive air showers (EAS), a huge nuclear-electromagnetic cascade induced by a primary particle in the atmosphere, and uses the obtained information to infer the properties of the original particle, its energy, type, direction, etc. Hence, the reliability of ultra-high energy cosmic ray analyses depends on the use of proper theoretical and phenomenological descriptions of the cascade processes.

The most natural way to predict atmospheric particle cascading in detail seems to be a direct Monte Carlo (MC) simulation of EAS development, like it is done, for example, in the CORSIKA program [1]. As very large computation times are required at ultra-high energy, an alternative procedure was developed to describe EAS development numerically, based on the solution of the corresponding cascade equations (CE). Combining this with an explicit MC simulation of the most energetic part of an EAS allows us to obtain accurate results both for average EAS characteristics and for their fluctuations in the CONEX program [2]. Combining the two programs not only a complete 3D simulation can be achieved with a reduced computation time but new analysis possibilities are open.

Not only simulation time and accuracy is important to analyze cosmic ray data, but how we can access to the results of the simulation is a key point of many new analysis methods.

After briefly describing COAST [3, 4], a recently added interface to CORSIKA data, and some new options in COR-SIKA, we present some observables, which can be obtained with these tools. In the third part of this article we discuss how the combination of CONEX and CORSIKA offers new options for air shower simulations.

#### 2 Improvements of CORSIKA

# 2.1 COAST

Informations produced during CORSIKA simulations can be accessed via various means. The traditional output is a binary output file containing the particles arriving at different observation levels (up to 10). The longitudinal development could be saved in addition. With time, more options were added usually using hbook histograms which were easy to handle but which couldn't be changed by the user.

Since 2005 a C++ interface is under development in Karlsruhe to simplify the management of simulation results from CORSIKA. COAST (COrsika dAta access Tools) [3, 4] has been developed to analyze the standard binary output file in a machine independent way together with an easy link to the ROOT analysis and graphical tools, and to have a direct access to all particles during the simulation to allow any user to develop his own output (histograms using ROOT or particle files). This allows to imagine completely new approaches in air shower analysis without changing the CORSIKA code itself.

A number of applications has already been developed using COAST and are publicly available :

- 3D view of shower track (see Fig. 1),
- Binary output file reader,
- · Histogramming to be used with REAS air shower radio signal simulation code [5],







Figure 1: Side view of particles arriving at ground (observation level at 1 km) using FLATOUT keyword (true T) (left-hand-side) or not (false F)(right-hand-side).

- Inclined observation plane option in CORSIKA,
- ROOT output for CORSIKA,

A user can develop his own output format or histogramming using the classes defined in COAST for the interface with CORSIKA. For instance, the particles can be saved which arrive on an arbitrary surface instead of the classical observation level, or on more than 10 observation levels.

## 2.2 Parallelization

To overcome the extreme long computing time for a single shower induced by an ultra-high energy primary particle the simulation task has to be split into many jobs which are treated in parallel on many cores of a computer cluster. In our approach installed as a new option the results of such parallel simulations are controled in a unique way by seeds for the random number generator given by the user. It is now possible to collect all particles above a user-defined threshold in an external file, which can be used to run all the sub-showers induced by these particles on different CPU's. If the seeds are well defined for each sub-shower, it is possible to reproduce the same shower under different technical conditions of the available computing resources. A challenge is the merging and handling of the huge final file containing all particles which arrive at ground.

To help book-keeping and for a better management of all the sub-showers on large clusters, there is the possibility to use CORSIKA as a subroutine of a master program which can distribute all the sub-showers on different CPU using MPI protocol. In that case, there is no need for an external file to save temporary stack.

As a side effect, an option has been added to introduce a particle or a list of particles anywhere in space independently of the shower axis. This can be used to study artificial showers having special features.

### 2.3 Additional Features of CORSIKA

A new feature for systematic studies of air shower physics is the additional information of the muons which arrive at the detector level. All relevant parameters of the (hadronic) grandmother and mother particles and of the muons are stored in four items of the extended additional muon information to derive their energy spectra, the distributions of their production positions (altitude rsp. distance from the shower axis), and their generation sequence. Similarly such informations can be obtained for the electromagnetic particles, where the mother and grandmother are those hadrons which induced the em-sub-shower from which the considered electron/positron rsp. gamma stems. For muons as well as for em-particles further parameters like the transverse momentum distribution obtained by the mother particles at their production may easily be calculated from the momenta components of grandmother and mother particles. All interesting features can be extracted by applying appropriate selections and cuts to one or several parameters of the extended additional muon information when filling histograms in a run with a suitably modified and extended version of the corsikaread\_history program.

Examples for the application of the EHISTORY option are given in the references [6, 7, 8]. A full description of this option is given in Ref. [9].

In case of simulation with the CURVED option, a new "FLATOUT" keyword has been added for the user to choose between a flat horizontal observation level using a Cartesian frame or a curved one (following Earth curvature) where the coordinates X and Y follow Earth surface. The difference can be seen in Fig. 1 and is really relevant only in case of very inclined showers.

Finally, the interface to FLUKA2011 [10] has been updated.

## **3** Hybrid Simulations

With the next release of CORSIKA, a new approach will be possible to analyse air shower data. Until now, only statistical analyses were possible because of the large showerby-shower fluctuations and the large computation time. Using hybrid simulation (CORSIKA + CONEX) together with the new hybrid detectors (fluorescence+surface (PAO [11], TA [12]), radio+surface (PAO, KASCADE [13]), ...) it is possible to study data shower-by-shower. Taking into account the number of possible applications and since the results should not change compared to the traditional approach, this version of CORSIKA is currently available on request as a test version. The public version will follow.

# 3.1 CONEX in CORSIKA

In order to have the best of CONEX and CORSIKA in one single program, we are using the method already implemented in SENECA [14] and outlined in Fig. 2. The COR-SIKA installation scheme and steering files are used to set the simulation parameters. Then, internally, these parameters are transferred to CONEX to start the MC simulation with the given primary energy. Depending on their energy, the secondary particles stay either in CONEX MC if  $E > E_{\text{thr}}$ , or go into the CORSIKA stack if  $E < E_{\text{low}}$ , or are used as source for 1-dimensional CE in the energy range between. When no more particles with  $E > E_{\rm thr}$ are stored on the CONEX stack, the CE are solved down to  $E_{\rm low}$ . The solution of the CE can be sampled into individual particles saved on the CORSIKA stack. At this point, a weight can be attributed to these particles to reduce the simulation time. Finally all these particles with  $E < E_{low}$ stored in the stack are tracked in CORSIKA as usual in a 3-dimensional space until they reach the observation level where they are stored in the chosen output file.



Figure 2: Implementation of CONEX in CORSIKA.

As a result, simulations can be done either in 1D (only the longitudinal profile) or in 3D (lateral distribution function (LDF)) depending on the parameters  $E_{\rm thr}$  and  $E_{\rm low}$  used. The simulation time depends mostly on the weight given to the particles sampled from the CE since the thresholds can not have arbitrary values in order to preserve the precision of the simulations. For instance, if  $E_{\rm low}$  is too low, the LDF will not be correctly reproduced. For an equivalent precision level, a minimum gain factor of 5 in time can be expected using this method instead of standard thinning.

#### 3.2 Shower-by-Shower Simulation

Unlike SENECA, in CORSIKA two different MC codes are used at the beginning and at the end of the shower. This means that two independent random number generators can be used simultaneously to generate different parts of the shower. In particular CONEX can be used in 1D mode to have a quick but accurate description of the longitudinal profile or total number of particles at ground and then the almost exactly same shower can be regenerated using even full 3D MC. Depending on the energy threshold used, many hadronic generations can be calculated in the CONEX MC reducing the fluctuations as much as possible. The user can easily control whether he wants to use or not the CE part and this will not change the beginning of the shower development since a dedicated random number sequence is used, as shown in Fig. 3.



Figure 3: Longitudinal distribution of charged particles for 3 vertical proton induced showers using the same random seed but using CE to the lowest energy (full line), only at intermediate energy (dashed line) or not at all (only MC) (dash-dotted line).

It allows many new possibilities to analyze air shower data and this method is already used for radio events [15] where the computation time is extremely large.

For instance, the arrival time distribution of muons and photons at 1000 m from the shower core is shown in Fig. 4

for inclined proton induced showers at  $10^{18}$  eV (average over 15 showers starting at the same height) generated with the combination of CORSIKA and CONEX using only MC with the thinning option or with the CE activated ( $E_{low} = 300$  GeV for hadrons and 10 GeV for electromagnetic particles). The results are in a very good agreement. The two bumps are due to the fact that we look at ground for an inclined shower without geometrical correction.



Figure 4: Arrival time distribution function at 1000 m for photons and muons from 60 degree inclined proton induced shower at  $10^{18}$  eV simulated with only MC (points) or with CE at intermediate energies (full line).

# 4 Conclusions

Latest releases of CORSIKA and COAST open the door to new analysis technics and a better understanding of shower observables [16].

In the near future, the fusion of CONEX in CORSIKA will allow fast detailed 3D simulations of ultra-high energy EAS. Combined with the parallelization of CORSIKA, simulation of unthinned showers corresponding to real observed events will even become feasible.

To have even more possibilities, CONEX can be adapted to run for different media (rock, ice, ...) to be able to run showers starting in one medium and finishing in a different one. This work is under development.

With LHC results, new versions of the EPOS [17], QGSJETII [18], and SIBYLL [19] will be released and added to CORSIKA. These should reduce the uncertainty due to hadronic interaction in air shower development and will help to a better understanding of the charged cosmic rays.

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