3D Air Shower Simulations Using CONEX in CORSIKA

Tanguy Pierog, Ralph Engel, and Dieter Heck

Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, Karlsruhe, Germany

***Abstract*. Interpretation of EAS measurements strongly depends on detailed air shower simulations. The reliability of these simulations is limited by our current knowledge and modeling of hadronic multiparticle production. Another severe limitation, though of technical nature, is the calculation time of Monte Carlo programs at very high energy. In this contribution we will present improvements implemented in the latest versions of the shower simulation codes CORSIKA and CONEX, addressing these limitations.**

***Keywords*: CORSIKA, CONEX, air-shower**

I. 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 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].

After briefly describing recent changes introduced in CORSIKA and CONEX in their latest release, we will present the latest results on important EAS observables obtained with these programs. In the second part of this article we will discuss how the two programs can be combined to achieve fast and accurate 3-dimensional EAS simulations. First results of this ongoing work are shown.

II. IMPROVEMENTS OF CORSIKA AND CONEX

One of the aims of releasing new versions of CORSIKA and CONEX is to provide the users with up-to-date versions of hadronic interaction models.

Two years ago, the new hadronic model EPOS 1.61 [3] brought a quite different philosophy in the hadronic models used for EAS simulations: Designed for high energy physics, unless others, EPOS is detailed enough to be compared to any type of accelerator data experiment. While the results on muon production were very promising [4], the model was shown to be incompatible with hadron data of the KASCADE experiment [5]. As a result of accounting for constraints given by cosmic ray experiments and further model developments to describe accelerator data, EPOS has been improved to version 1.99, which has been introduced this year in both CORSIKA and CONEX as new hadronic interaction model. Some results are presented in the following. Details on EPOS 1.99 are given in [6].

Concerning the particle tracking algorithms, the most important improvement in the last release of CORSIKA (6.900) is the possibility to follow [7] charmed particles produced by QGSJET01 [8] and DPMJET 2.55 [9]. Only with increasing collision energy above 10^{16} eV the production cross section becomes large enough [10], [11] for a noticeable number of charmed hadrons. In the new CHARM option these particles are tracked to the point of decay. As their life times are generally short ($\approx 10^{-12}$ sec) and their interaction cross sections unknown, currently only the decay is considered, neglecting all possible interactions. The new extension of CORSIKA introduces the masses and life times of all ground states of charmed hadrons, as well as of their first excited resonance states, and of the strange charmed

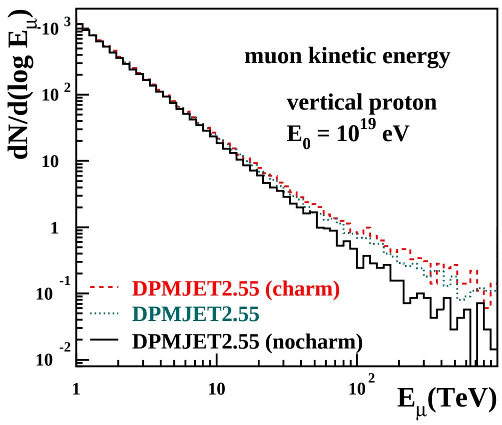

Fig. 1. Sensitivity of muon energy spectra influenced to charm particle production using standard DPMJET (charmed particles decay at production, dotted line), with charm production and tracking (dashed line), and with charm production suppressed (full line).

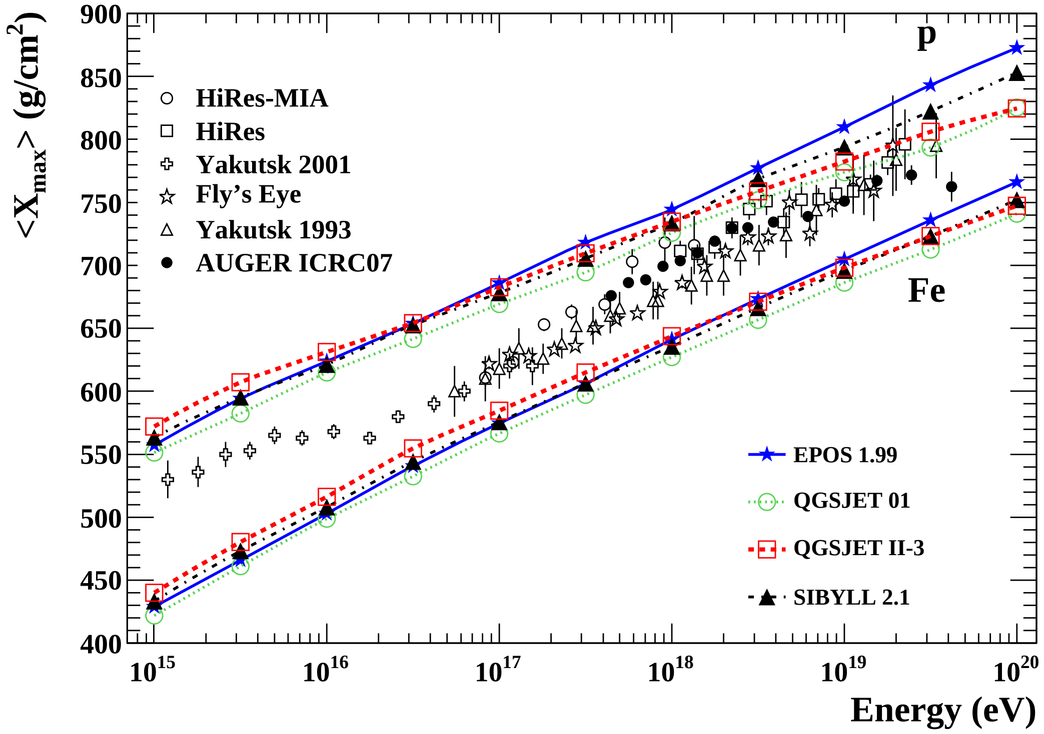

Fig. 2. Mean X_{max} for proton and iron induced showers as a function of the primary energy. Predictions of different high-energy hadronic interaction models, QGSJET01 (dotted), QGSJET II-3 (dashed), SIBYLL 2.1 (dashed-dotted), and EPOS 1.99 (solid), are compared to data. Refs. to the data can be found in [13].

hadrons. The decays are treated by the PYTHIA package [12] which is coupled [7] with CORSIKA.

The number of high energy muons in EAS, which emerge at a low percentage from the decay of charmed mesons, is sensitive to charm production. Fig. 1 shows the muon energy spectra of vertical proton induced EAS of 10^{19} eV primary energy (averaged over 100 EAS), one set simulated with the standard DPMJET/GHEISHA [14] interaction models. In the standard version DPMJET produces charmed particles, which decay immediately at the production vertex and are implicitly treated in the interaction. In a second set of showers (denoted by 'charm') the produced charmed hadrons are transported to the point of their decay. In a third set the charm production is suppressed artificially (denoted by 'nocharm'). The influence on the muon energy spectra is visible only above 10 TeV, in average only very few additional muons are produced by the charmed mesons.

A technical improvement was achieved in CORSIKA by replacing the shell script `corsika-install` by the perl program `coconut` to manage in a portable way the `autoconf/automake` tools for the installation and selection of options in CORSIKA. Options are selected by a shell script using `autoconf` and standard C preprocessor commands in the CORSIKA source code.

Finally, the interface to FLUKA2008.3b [15] has been updated.

III. Latest results

In the following EAS simulation results using EPOS 1.99 [6] and QGSJET II-3 [16] are presented and compared to former results using QGSJET01 [8] or SIBYLL 2.1 [17], [18].

As shown in Fig. 2, the mean depth of shower maximum, X_{max}, for proton and iron induced showers simulated with CONEX is quite different for EPOS 1.99. EPOS proton induced showers show a significantly higher elongation than QGSJET II. Above 10^{19} eV, both QGSJET01 and QGSJET II elongation rates decrease due to the very large multiplicity of these models at ultra-high energy. Below 10^{18} eV, an analysis of X_{max} data would lead to a composition of primary cosmic rays that is heavier using QGSJET II compared to EPOS. Above 10^{18} eV the situation is reversed.

In Fig. 3 CONEX-based estimates for the value of the Cherenkov signal in Auger tanks [19] due to muon component, $S_\mu(1000\,\text{m})$, are plotted as a function of the zenith angle. The tank signal has been simulated in a simplified way, that is why only the relative differences between the model results are shown here (reference is proton induced showers with QGSJET II). Due to a much larger muon number at ground in EPOS [4], the density at 1 km is higher by about 25% for proton induced showers and up to 90% in case of iron induced showers if compared to the proton prediction of QGSJET II. Such a difference is of crucial importance for the reconstruction

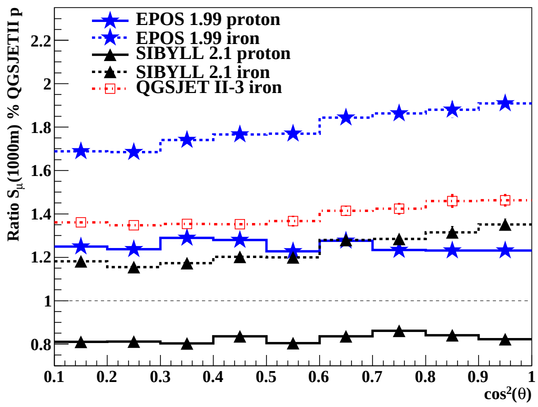

Fig. 3. Muon contribution to S(1000m) as measured by the Pierre Auger Observatory for 10^{19} eV air showers simulated with different high-energy hadronic interaction models and primary mass: EPOS 1.99 (stars) proton (full) and iron (dashed), SIBYLL 2.1 (triangles) proton (full) and iron (dashed), and QGSJET II-3 iron (squares dashed-dotted), relative to proton with QGSJET II-3.

of the primary energy and composition with ground array experiments. Compared to other models, using EPOS would decrease the energy reconstructed from lateral densities and could lead to a more consistent cosmic ray composition obtained from muon number and mean X_{max} data [20]. On the other hand, SIBYLL 2.1 shows about a 20% lower muon signal than QGSJET II.

The higher muon number from EPOS is due mainly to a larger baryon-antibaryon pair production rate in the individual hadronic interactions in showers. By predicting more baryons, more energy is kept in the hadronic shower component even at low energy. As a consequence, the calorimetric energy – as measured by fluorescence light detectors – is reduced since more energy is transferred to neutrinos and muons. In Fig. 4 the conversion factor from the visible calorimetric energy to the real energy is plotted as a function of the primary energy of the showers. As expected, EPOS 1.99 shows a conversion factor which is up to 2% higher than QGSJET II. SIBYLL results (not shown) are very similar to QGSJET II.

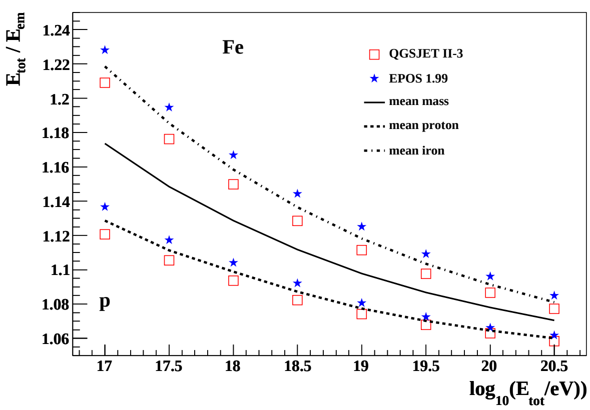

Fig. 4. Mean factor for the conversion of observed (calorimetric) energy to total energy for iron (dashed-dotted) or proton (dashed) induced showers. The conversion factor is shown for QGSJET II-3 (squares) and EPOS 1.99 (stars). The mean conversion factor (solid line) is calculated by averaging all proton and iron predictions.

IV. Outlook

For the next release of CORSIKA, two important improvements are in preparation. First of all work is in progress to run CONEX in the framework of CORSIKA both for 1-dimensional fast simulations and detailed 3-dimensional simulations. Secondly, CORSIKA is being modified to take advantage of modern computing clusters by simulating showers in a controlled parallel way.

A. 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 [21] and outlined in Fig. 5. The CORSIKA 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 $E > E_{\rm thr}$, or go into the CORSIKA stack if $E < E_{\rm low}$, or are used as source for 1-dimensional CE in 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 $E < E_{\rm low}$ 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.

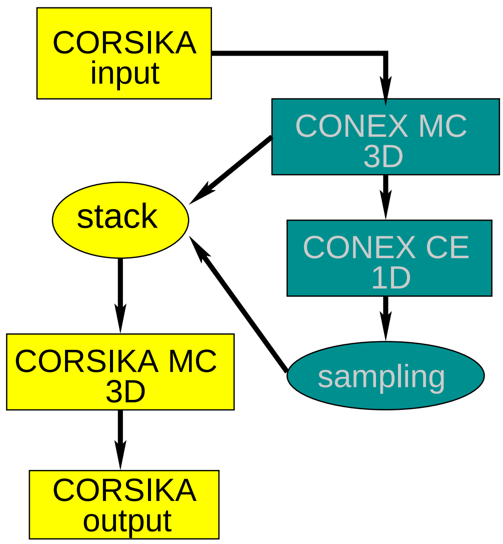

Fig. 5. Implementation of CONEX in CORSIKA.

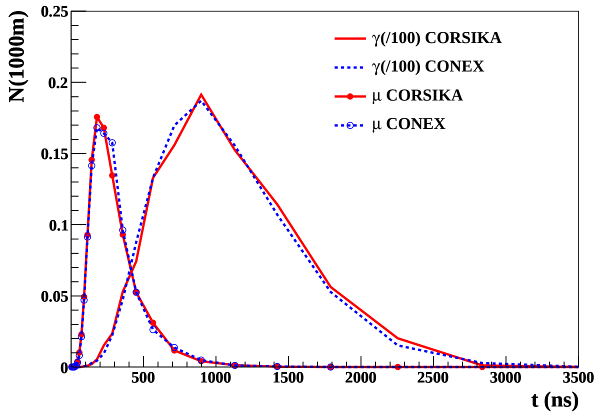

Fig. 6. Arrival time distribution function at 1000 m for photons and muons from vertical proton induced shower at 10^{19} eV simulated with CORSIKA (full line only MC) or with CONEX in CORSIKA (dashed line using CE at intermediate energies).

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_{thr} and E_{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_{low} is too low, the LDF will not be correctly reproduced. For an equivalent precision level, a gain factor of 10 in time can be expected using this method instead of standard thinning. As a first result, the arrival time distribution of muons and photons (divided by 100) at 1000 m from the shower core is shown Fig. 6 for vertical proton induced showers at 10^{19} eV (average over many showers) generated with the usual CORSIKA thinning option (full lines) and with the CONEX option ($E_{\mathrm{low}} = 10$ TeV for hadrons and 10 GeV for electromagnetic particles). The results are in a very good agreement.

B. Parallelization

To perform parallel simulations of a single shower in which the results are controlled in a unique way by seeds for the random number generator given by the user, a new option is under development. It will be possible to save all particles above a user-defined threshold in an external file, which can be used to run all the subshowers induced by these particles on different CPU's. If the seeds are well defined for each subshower, it is possible to reproduce the same shower under different technical conditions.

V. Conclusions

New versions of CORSIKA and CONEX have been released recently with an update of the new hadronic interaction model EPOS 1.99. The available hadronic interaction models differ in several important aspects in the approach of reproducing data. SIBYLL 2.1 and QGSJET 01 are fast and simple models focusing on the description of the main observables a priori needed for EAS simulations. In QGSJET II-3, high parton density effects are treated by re-summing enhanced Pomeron graphs to all orders, but energy conservation at amplitude level is not implemented. On the other hand, in EPOS, energy conservation at amplitude level is fully implemented, but high-density effects are treated by a phenomenological approach. EPOS is particularly well-tuned to describe available accelerator data including heavy ion collisions measured at RHIC. The differences of the model predictions are large: At high energy, proton induced air showers simulated with EPOS have even more muons at ground than iron induced showers simulated with QGSJET II and air showers developed deeper in the atmosphere.

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.

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