

Extensive Air Shower Simulation Program CONEX: Matching Monte Carlo and Numerical Methods

M. Alekseeva^a, T. Bergmann^b, V. Chernatkin^c, R. Engel^b, D. Heck^b,
N. Kalmykov^a, S. Ostapchenko^{b,a}, T. Pierog^b and K. Werner^c

(a) D.V. Skobel'syn Institute of Nuclear Physics, Moscow State University, 119992 Moscow, Russia

(b) Forschungszentrum Karlsruhe, Institut für Kernphysik, 76021 Karlsruhe, Germany

(c) SUBATECH, Université de Nantes – IN2P3/CNRS – Ecole des Mines, Nantes, France

Presenter: S. Ostapchenko (serguei@ik.fzk.de), ger-ostapchenko-S-abs2-he14-poster

We discuss the structure of new extensive air shower simulation code CONEX and demonstrate the advantages of the hybrid air shower calculation scheme employed. The latter combines an explicit Monte Carlo simulation of the most energetic part of the particle cascade in the atmosphere with a numerical treatment of secondary sub-cascades of smaller energies, using a system of corresponding integro-differential equations. Special attention is paid to the accuracy and the efficiency of the method. The results of the calculations, e.g., shower size profile, number of muons, particle energy spectra, are compared to the ones obtained using the traditional Monte Carlo approach, and to calculations with the CORSIKA program. Finally, we discuss possible applications of the code and the prospects for its further development.

1. Introduction

In contemporary high energy cosmic ray (CR) experiments Monte Carlo (MC) simulations of extensive air shower (EAS) development constitute an important part of data analysis procedures. Corresponding simulation tools, like the CORSIKA [1] and AIRES [2] programs, are applied to establish relations between the measured EAS characteristics and the properties of primary CR particles. However, at very high energies, such calculations are very time-consuming and therefore have to be optimized. A popular method is to replace the full MC treatment of EAS development by some weighted sampling procedures, e.g., to apply the "thinning" method [3]. A promising alternative is to employ so-called hybrid procedures, which combine a direct MC simulation of the most energetic part of the air shower, for particle energies exceeding some energy threshold E_{thr} (typically chosen to be a factor 100 smaller than the energy of the primary particle), with numerical description of particle sub-cascades of smaller energies, based on the solution of corresponding nuclear-electro-magnetic cascade equations. Such a method allows one to reduce drastically the EAS calculation time, while having the same or in some cases even superior precision compared to standard methods.

Here we discuss a new EAS simulation program of that kind – CONEX [4]. The MC treatment of high energy ($E > E_{thr}$) hadronic and electro-magnetic (e/m) cascading processes in CONEX is very similar to its implementation in CORSIKA program: one follows the propagation, interactions, and decays (when relevant) of different hadrons, electrons (positrons), photons, and muons. There, hadronic interactions are treated optionally with the NEXUS [5], QGSJET [6], or SIBYLL [7] models (at low energies the GHEISHA program [8] can be employed as well), whereas the e/m part is handled by means of the EGS4 code [9], supplemented by an account for the Landau-Pomeranchuk-Migdal effect and for the photo-production process. All particles falling below the chosen energy threshold are stored to form the initial condition (so-called source term) for the cascade equations. Finally, further development of the complete nuclear-e/m cascade at sub-threshold energies is obtained by solving a system of integro-differential equations for the process, with the initial condition defined by the *multi-particle* source term, the latter having been formed as the result of the above-threshold cascade, i.e. *individually* for each shower. More detailed description of the corresponding procedures is given elsewhere [4] (see also [10, 11]).

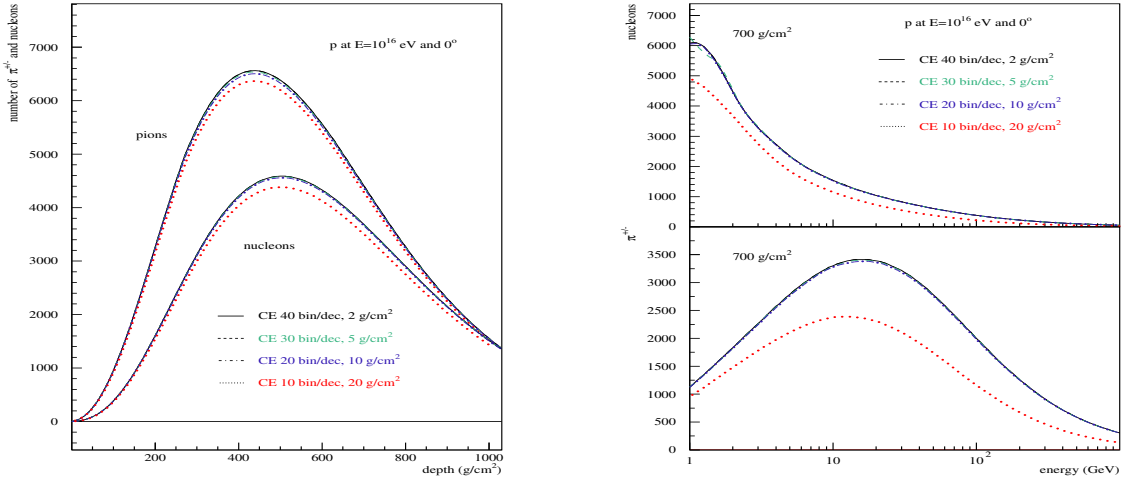


Figure 1. Longitudinal profiles (left) and energy spectra at 700 g/cm^2 (right) of nucleons and charged pions for proton-initiated vertical EAS of energy 10^{16} eV as calculated for different binning options using the numerical procedure (CE) with the QGSJET model.

2. Air shower characteristics

To illustrate the stability of our numerical procedure, we plot in Fig. 1 longitudinal profiles and energy spectra at 700 g/cm^2 of nucleons and charged pions for proton-initiated vertical EAS of energy 10^{16} eV for different binning options. Hadronic interactions have been treated using the QGSJET model. We choose correspondingly for the number of bins per energy decade and for the depth bin width (in g/cm^2) the following values: 40 and 2, 30 and 5, 20 and 10, 10 and 20. As seen from the Figure, we obtain nearly identical results in all cases, with the exception of the last, rather crude binning.

In general, the numerical procedure for the solution of e/m cascade equations is characterized by even better stability and allows to employ a more crude binning. Nevertheless, our default choice (to be applied for the calculations below) is rather conservative one, corresponding to 20 bins per energy decade and to 10 g/cm^2 step size in slant depth for both hadronic and e/m numerical procedures. In hybrid mode, the cutoff between the MC and the numerical part is set to $E_{\text{thr}} = 10^{-2} E_0$, E_0 being the primary energy. Furthermore, for comparison with CORSIKA in the following we apply GHEISHA and QGSJET for hadronic interactions below and above 80 MeV correspondingly. The typical computing time for proton-induced EAS of energy 10^{19} eV is one minute per shower using QGSJET or SIBYLL as high energy hadronic models.

In Fig. 2 we compare longitudinal profiles and energy spectra at 700 and 1000 g/cm^2 of charged pions and muons of energies above 1 GeV for proton-initiated vertical EAS of energy 10^{18} eV as calculated using the MC, numerical, and hybrid procedures, and with the CORSIKA program. In Fig. 3(left) we perform a similar comparison for longitudinal profiles of charged particles and photons for proton-initiated vertical EAS of energy 10^{18} eV . In addition, in Fig. 3(right) shown the energy spectra at 700 g/cm^2 of electrons, positrons, and photons for photon-initiated 10^{16} eV shower. Evidently, we obtain a very good agreement between the different methods.

Finally, we may test whether the employed hybrid scheme describes correctly EAS fluctuations. In Fig. 4(left) we plot the distribution for the deviation of the shower maximum position from its average value, $X_{\text{max}} -$

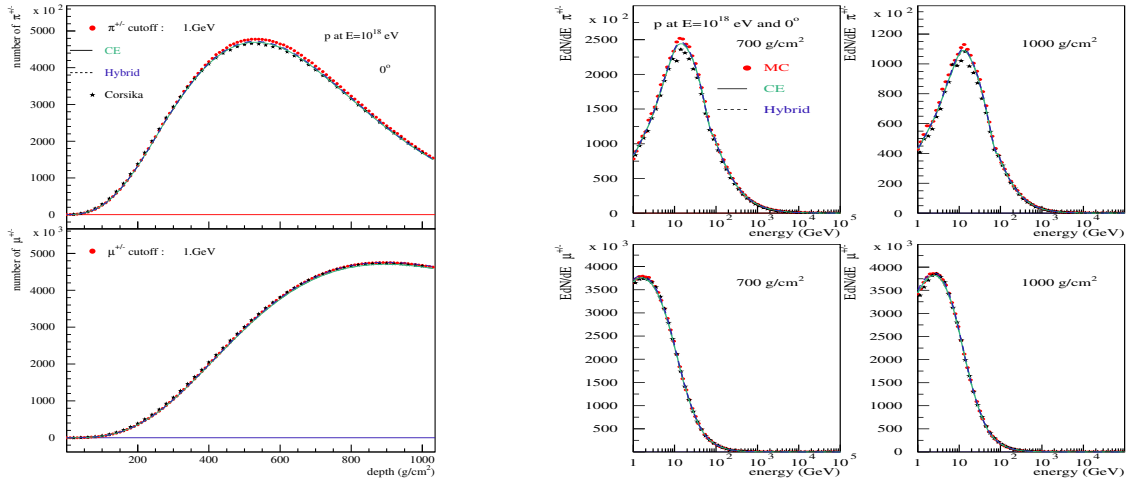


Figure 2. Longitudinal profiles (left) and energy spectra at 700 and 1000 g/cm² (right) of charged pions and muons of energies above 1 GeV for proton-initiated vertical EAS of energy 10¹⁸ eV as calculated using the MC (points), numerical (full line), and hybrid (dashed line) procedures in comparison to CORSIKA results (stars). The GHEISHA and QGSJET hadronic interaction models have been used below and above 80 MeV correspondingly.

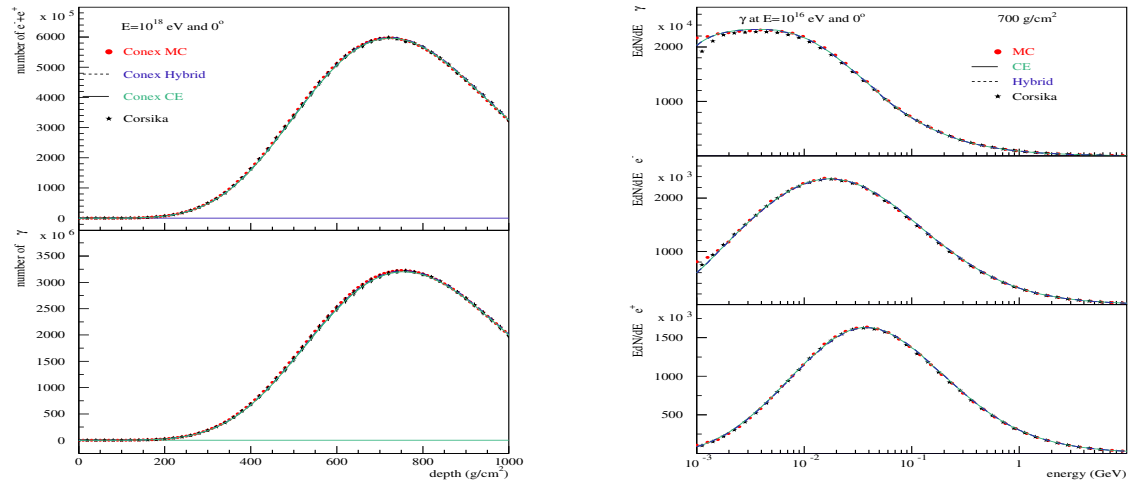


Figure 3. Left: longitudinal profiles of e^\pm and γ of energies above 1 MeV for 10¹⁸ eV p -initiated EAS; right: energy spectra of photons, electrons, and positrons at 700 g/cm² for 10¹⁶ eV γ -induced shower. Calculations with CONEX MC (points), numerical (full line), and hybrid (dashed line) procedures in comparison to CORSIKA results (stars).

$\langle X_{\max} \rangle$, as calculated with the CONEX and CORSIKA programs. One observes an excellent agreement between the two results. In Fig. 4(right) we investigate the sensitivity of the obtained X_{\max} fluctuations to the choice of the threshold between the MC and numerical treatment. It is easy to see that these fluctuations are in general well described even for a rather high threshold value, $E_{\text{thr}} \simeq E_0$, being essentially defined by the propagation and interaction of the primary particle.

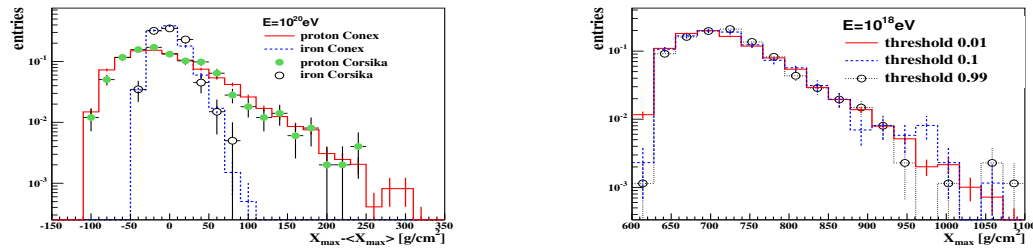


Figure 4. Left: fluctuations of the depth of shower maximum around the mean value $\langle X_{\max} \rangle$ for proton- and iron-initiated EAS of energy 10^{20} eV as calculated with the CONEX program (histograms) in comparison to CORSIKA results (points). Right: distribution of the depth of shower maximum for proton-initiated EAS of energy 10^{18} eV as calculated with the CONEX program for different thresholds between the MC and numerical parts.

3. Conclusions

We have demonstrated that the developed hybrid EAS simulation program CONEX allows us to achieve the same accuracy in describing basic shower characteristics and their fluctuations as the standard MC codes, e.g., CORSIKA code, while allowing to reduce considerably the calculation time. The results obtained with different methods, i.e. using MC, numerical, and hybrid procedures agree well with each other. While the present version of CONEX is restricted to one-dimensional (longitudinal) EAS description, further work is in progress to extend the scheme to the full three-dimensional EAS treatment [12]. On the other hand, already now the program is perfectly suitable for certain practical applications, in particular, in connection to high energy cosmic ray studies with fluorescence detectors, allowing reliable calculations of both charged particle energy spectra at various depths in the atmosphere, and of longitudinal profiles of particle energy deposits, as discussed in more detail in [13]. This gives the possibility to perform fast and accurate calculations of fluorescence and Cherenkov light production in air showers, without any need for parameterizations of shower profiles.

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