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RECENT EXTENSIONS TO THE AIR SHOWER SIMULATION PROGRAM CORSIKA

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ABSTRACT

CORSIKA is a Monte Carlo program simulating the evolution of extensive air showers in the atmosphere initiated by photons, nucleons, or nuclei. The new version 5.20 was released in March 1997. The major modifications with respect to version 4.5 concern: Treatment of high energy hadronic interactions by 5 different models, corresponding inelastic hadronic cross-sections for mean free path calculation, extension to highest energies (10^{20} eV) including a thinning algorithm, improved muon tracking comprising muon bremsstrahlung and direct e^+e^- pair production processes, and a version running on PCs under LINUX.

INTRODUCTION

The simulation program CORSIKA (**CO**smic **R**ay **SI**mulation for **KA**SCADE) has been developed (Capdevielle et al., 1992, Knapp and Heck, 1993) to analyze extensive air shower (EAS) measurements performed with the KASCADE experiment (Klages et al., 1997). Since the first version from 1990 many improvements and extensions have been added (Knapp et al., 1995), to meet requirements of the KASCADE experiment and of a wide-spread user community involved in EAS and neutrino experiments.

HADRONIC INTERACTION MODELS

One of the major uncertainties in Monte Carlo simulation of EAS is the dependence upon the hadronic interaction models. Usually these models are tuned to fit collider data, but unfortunately none of the collider experiments registers particles emitted into the extreme forward direction, as they disappear in the beam pipe. These particles carry most of the hadronic energy and are of highest importance in the development of EAS, since they transport a high energy fraction deep into the atmosphere. Moreover, when extrapolating to energies exceeding those accessible by accelerators, one has to rely on theoretical guidelines. In the past several phenomenological event generators have been built, based on simple models or on more elaborate theoretical foundations. Most of them reproduce the collider data but their predictions differ when applied to typical EAS energies and small angles.

To estimate the systematic errors due to the hadronic interaction model, we have implemented in CORSIKA five hadronic interaction models for energies > 80 GeV per nucleon. Besides the models HDPM (Capdevielle, 1989, Capdevielle et al., 1992) and VENUS (Werner, 1993), we have added SIBYLL (Fletcher et al., 1994, Engel et al., 1992), QGSJET (Kalmykov and Ostapchenko, 1993), and DPMJET (Ranft, 1995). This enables a systematic comparison of all five models within the environment of the CORSIKA program (Knapp et al., 1996).

VENUS, QGSJET, and DPMJET model hadronic interactions of nucleons and nuclei on the basis of the Gribov-Regge theory, which successfully describes elastic scattering and the total hadronic cross-section as a function of energy. The rise of the cross-sections is accounted for by the multiple exchange of *supercritical pomerons*. Inelastic processes are described by *cut pomerons* leading to two color strings each, which fragment subsequently to color neutral

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hadrons. While this is common for all Gribov-Regge models they differ in the way the production and decay of the strings is realized. SIBYLL is a *minijet* model. It simulates a hadronic reaction as a combination of an underlying soft collision in which two strings are generated and a number of minijet pairs leading to additional pairs of strings with higher $p_\perp$ endpoints. HDPM is a purely phenomenological model which uses detailed parameterizations of $p\bar{p}$ collider data for particle production. The extension to reactions with nuclei and to energies beyond the collider energy range are somewhat arbitrary.

The Gribov-Regge type models simulate nucleus-nucleus collisions in great detail allowing for multiple interactions of nucleons from projectile and target. HDPM and SIBYLL employ the superposition model assuming an independent reaction for each of the projectile nucleon.

QGSJET, DPMJET, and SIBYLL account for minijet production, which becomes dominant at higher energies and leads to increasing cross-sections and more high $p_\perp$ particles. While in QGSJET and DPMJET minijets contribute only partially to the rise of the cross-section, they are solely responsible for it in SIBYLL.

VENUS is the only model taking into account the interactions of intermediate strings and secondary hadrons with each other, leading to better agreement with final states as measured in collider experiments at the expense of longer computing times.

Each of the models utilizes its own inelastic hadronic cross-sections, which can be selected for the calculation of the mean free path to the next collision. Apart from SIBYLL the nucleus-air cross-sections are calculated from the model specific pp cross-sections using the Glauber probabilities calculated by Capdevielle et al. (1992). The choice of cross-sections is independent of the model chosen for the particle production. The influence of the cross-sections on the EAS development is discussed by Knapp et al. (1997).

DPMJET and optionally VENUS describe the production of charmed hadrons. Since these cannot be handled in the tracking and decay parts of CORSIKA, they are treated as baryons or mesons with charm replaced by strangeness. QGSJET and SIBYLL are technically working up to energies of $> 10^{11}$ GeV, while HDPM, VENUS, and DPMJET are limited to the maximum energies given in Table 1, where the basic features of the five models are summarized.

Depending on the complexity of the interaction program, the memory needed and the computing times of the interaction models differ considerably. Table 1 shows also the requirements for the various models on a DEC AXP machine (175 MHz). The computing times were measured for 500 vertical proton showers of $E_0 = 10^{15}$ eV. They comprise the hadronic and muonic part of the showers and the analytic treatment of the electromagnetic subcascades with the NKG formulas. When using EGS (Nelson et al., 1985) the computing times are dominated by the electromagnetic component and the differences between the hadronic models are small.

Table 1: Basic Features of the Interaction Models Used

	HDPM	SIBYLL	QGSJET	VENUS	DPMJET
Gibov-Regge			+	+	+
Minijets		+	+		+
Sec. Interactions				+	
N-N Interaction			+	+	+
Superposition	+	+			
Max. Energy (GeV)	10^8	$> 10^{11}$	$> 10^{11}$	5×10^7	10^9
Memory (Mbyte)	7.6	8.3	9.7	21	52
CPU Time[1] (min)	500	371	484	2250	1310

[1] $E_\mu, E_h > 0.3$ GeV, 110 m a.s.l., NKG option, 500 showers.

NUCLEAR FRAGMENTATION

For all hadronic interaction models the fragmentation scheme of primary nuclei can be selected. The options are total fragmentation (i.e. all nucleons are released), no fragmentation (i.e. the unwounded nucleons are retained in one residual nucleus), or a realistic fragmentation in between the extreme cases. In the last case depending on the hadronic model one or more spectator fragments are formed. They evaporate further nucleons or α-particles with transverse momenta resulting from the Fermi motion of the nucleons in the primary nucleus.

HIGHEST ENERGIES

With QGSJET and SIBYLL two hadronic interaction models are available, which are able to simulate interactions for $E > 10^{20}$ eV, i.e. the range of the highest energies ever measured in cosmic rays. To run CORSIKA up to these energies the treatment of electromagnetic interactions with EGS was upgraded and a thinning mechanism was introduced to restrict the computing times to a manageable amount.

Electromagnetic Interactions

The electromagnetic cross-sections and branching ratios, tabulated in the program, have been extended to cover now about 14 orders of magnitude from 3 MeV up to 10^{20} eV. In addition, the EGS internal precision for trigonometric functions has been improved by a factor of 20. The Landau-Pomeranchuk-Migdal (LPM) effect, which reduces the bremsstrahlung and pair production cross-sections at high energies and modifies the secondary particles' energy distribution, is not taken into account. In the thin atmosphere the LPM effect becomes important for photon showers above 10^{18} eV, only.

Thin Sampling

In Monte Carlo programs for EAS simulation the computing times roughly scale with the primary energy, thus becoming excessive for showers initiated by particles with $E > 10^{16}$ eV. A way out of this problem is the 'thin sampling' or 'variance reduction' (Hillas, 1997). Below an adjustable fraction of the primary energy (thinning level $\varepsilon_{th} = E/E_0$) only one of the secondary particles is followed, selected at random according to its energy, while all other secondaries are discarded. An appropriate weight is attributed to the surviving particle to conserve energy. By this means only a constant number of particles must be followed in the low energy portion of EAS instead of an exponentially growing number. This mechanism was implemented into EGS (according to Nelson et al., 1985) and into the hadronic part. In case of thinning the whole structure of the particle output file is modified to contain the additional weight parameter. If thinning is not active the structure of the particle output remains unchanged. Table 2 shows the dependence of the computing time on ε_{th} for a vertical 10^{15} eV proton shower using QGSJET, EGS, and the standard CORSIKA parameters.

Table 2: Computing Times for Various Thinning Levels

ε_{th}	none	10^{-6}	10^{-5}	10^{-4}	10^{-3}
Time (min)	98	24	5.6	1.5	0.38

MUON TRACKING

The tracking of muons was refined. Besides the continuous energy loss of muons by ionization the explicit production of muon bremsstrahlung and e^+e^- pairs is included. The muon multiple scattering is treated optionally according to Molière's theory or by the Gaussian approximation as implemented in the detector Monte Carlo code GEANT (CERN, 1993). For detailed studies of the muon component the coordinates and momenta of the muon's origin can be obtained beside the standard particle informations.

DECAYS

The Dalitz decay $\pi^0 \rightarrow e^+e^-\gamma$ (branching ratio 1.2%) was implemented into CORSIKA, which contains now all decay modes of instable particles with branching ratios down to 1%.

PROGRAM HANDLING

CMZ Extraction Macro. CORSIKA is distributed as a .car file to be handled by the CMZ source code management system (CERN, 1994). To facilitate the extraction of a compilable FORTRAN file with the desired options, a macro is included, which guides the user interactively and prevents the selection of conflicting options.

LINUX Version. There is a new CORSIKA version running on PCs under LINUX.

Data Base File. For each simulation run a data base file can be created containing the essential input parameters of the run. This file may serve as input for a data base program keeping track of the simulations performed.

Shower Plots. With the PLOT option the start and arrival coordinates of each track element are written to separate files for hadrons, muons, and electromagnetic particles. With an appropriate user program, these files can be read to produce plots of a shower.

Program Distribution. The CORSIKA program files and an up to date version of the User's Guide (Knapp and Heck, 1993) can be obtained via anonymous ftp from ftp@ik3al1.fzk.de (with restricted access). Interested users should contact the authors for further details.

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