The Cosmic Air Shower Simulation Program C O R S I K A*

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Abstract

CORSIKA is a detailed program to simulate the evolution of extensive air showers initiated by high energy cosmic ray particles. Parameter sets are available to describe the atmosphere at various climatic zones and season. Details of the particle tracking are explained. The hadronic interactions at high energies may be simulated by six reaction models alternatively: The VENUS, QGSJET, and DPMJET models are based on the Gribov-Regge theory, SIBYLL is a minijet model, and the phenomenological generator HDPM is adjusted to experimental data wherever possible. Recently NEXUS has been added, but it still needs improvements to agree with extensive air shower data. The influence of those models on observable quantities of air showers are discussed with emphasis to the muonic component.

1 Introduction

CORSIKA (**CO**smic **R**ay **SI**mulation for **KA**scade) is a detailed Monte Carlo program to study the evolution of extensive air showers (EAS) in the atmosphere initiated by various cosmic ray particles. Originally it was developed to perform simulations for the KASCADE experiment [1] at Karlsruhe and has been refined considerably since its first version in 1989. Meanwhile it has developed into a tool that is used by many groups worldwide. The prediction of muon energy spectra, multiplicities and densities of EAS is a well suited application of CORSIKA, and such data may explain the high multiplicity events seen by the ALEPH-detector [2]. A detailed description of the physics incorporated in CORSIKA is given in Ref. [3], technical details on the handling of the program are described in [4].

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2 Global parameters and particle tracking

To start CORSIKA the primary's type, energy and angle must be defined. To follow the evolution of EAS through the atmosphere, the medium air must be defined. Various sets of parameters are available, which describe the atmosphere by a 5-layer model with varying barometric density exponents (transparency 5). Besides the U.S. standard atmosphere, there exist parameter sets which respect the position on the globe and the seasonal influence, e.g. for tropical, subtropical, mid-latitude, South pole and middle Europe (transparency 6). The composition of air is described by the volume fractions of 78.1%, 21.0%, and 0.9% for N_2, O_2, and Ar, respectively. The absolute flux of cosmic ray particles as well as their elemental composition is not incorporated into the program, rather it must be specified together with the exponent, which characterizes the energy spectrum steeply falling with increasing energy (transparency 3).

Neglecting the Earth's curvature a flat atmosphere is adopted, therefore the zenith angle must be limited to $\theta < 70^o$. For large zenith angles $\theta > 70^o$ the Earth's curvature must be taken into account (transparency 7 & 8). For simplicity the Cartesian coordinate system is kept, but the horizontal step size is limited to $< 20\ km$. Longer transport distances are chopped into appropriate segments to be treated in a local flat atmosphere. After each traversed segment the particle coordinates are transferred into the next local Cartesian coordinate system with its vertical axis pointing to the middle of Earth. Thus the curved Earth's surface is approximated piece by piece by flat segments with limited horizontal extension.

Within the program the leptons γ, $e^\pm$, $\mu^\pm$, (electronic and muonic neutrinos optionally), the mesons π^o, $\pi^\pm$, $K^o_{S/L}$, $K^\pm$, and η, the nucleons, the strange baryons with strangeness $|s| \leq 3$, and the corresponding anti-baryons are followed (transparency 4). Additionally nuclei with mass number $A \leq 60$ can be treated. All these particles are tracked explicitly and may undergo interactions. For instable particles all decay modes with branching ratios down to the 1% level are taken into account with correct kinematics also in 3-body decays. Charmed particles are not tracked explicitly, rather they decay immediately within those hadronic interaction programs which are able to simulate their production.

For each particle its transportation range is estimated. For interaction this is determined by the appropriate cross-section, for decay the particle life time limits the range. Except for stable particles both ranges are evaluated individually with separate random numbers, and the shorter range is taken for the actual path length. By these means automatically the further fate (interaction or decay) of the particle is decided. In the range determination for decay the ionization energy loss of charged particles is considered, which especially for muons with their long life time and low interaction cross-section (only bremsstrahlung and e^+e^--pair production are considered) results in markedly reduced muon fluxes below $\approx 10\ GeV$. This treatment slightly favors the decay of charged pions - the main source of muons - at expense of pion induced interactions, dependent on energy and height of origin.

During transport the deflection of charged particles by the Earth's magnetic field is considered. In the middle of each muon transportation step multiple scattering is imitated by one single scatter event with an appropriate scattering angle, which is determined by the traversed matter and the muon's energy. For each particle reaching a detector level its coordinates including momentum components and arrival time are stored on disk for later analysis or for use as input to a detector simulation program which in case of underground detectors describes also the muon penetration through rock.

In CORSIKA electrons and gammas are treated separately by a tailored version of the EGS4 Monte Carlo code [5] and/or less detailed but much faster by analytical NKG-formulas. Optionally Cherenkov photons may be generated. The interaction of hadrons with energies below $E_{lab} < 80\ GeV$ is simulated by the GHEISHA code [6], which is a program well proved up to some hundred GeV and implemented also in the wide-spread detector Monte Carlo code GEANT [7]. For hadronic interactions at higher energies 6 different reaction codes are available, as described in the following section.

3 Hadronic interaction models

The largest uncertainties in numerical simulation of EAS with primary energies above some TeV are introduced by the models which describe the hadronic interactions. Especially when extrapolating to the highest energies, where the collision energies exceed those accessible by accelerators, one has to rely on theoretical guidelines to simulate the interactions. An additional uncertainty stems from those secondary particles which carry away the highest energies. They are emitted into the extreme forward direction at small angles and are not observable in collider experiments, rather they disappear in the beam pipe of the accelerators (transparency 9). A comparison [8, 9] of EAS simulated with 5 different hadronic interaction models embedded in the identical CORSIKA environment gives an idea on the uncertainties introduced by interaction models. The VENUS (vers. 4.12) [10], QGSJET [11], and DPMJET (vers. 2.4) [12] models are based on Gribov-Regge theory, SIBYLL (vers. 1.6) [13] is a minijet model, and the phenomenological generator HDPM (described in the Appendix of [3]) is adjusted to experimental data wherever possible. The most recent NEXUS model [14, 15] is in a too early state to present results gained with it. Basic features of the 6 models are given in (transparency 10). Despite the availability of experimental data it is surprising to find differences of $\approx 10\%$ in the adopted p-air cross-sections below $p_{lab} \leq 10^5\ GeV/c$, as shown in (transparency 12) together with experimental points gained by air-shower measurements (see Refs. [19, 20, 21, 22, 23]).

Essential experimental observations of p-$\overline{p}$ interactions to be reproduced by the models are, besides others: The increase of the average charged particle multiplicity with increasing energy (transparency 13), the scatter of the number of emitted charged particles around the mean value according to a negative binomial distribution (transparency 14), and the rapidity distribution of emitted charged particles for various energies (transparency 15). A comparison of the pseudo-rapidity with recent experimental data [18] at $E_{cm} = 630\ GeV$ is shown in (transparency 16). The average transverse momentum as function of energy for $p\overline{p}$ interactions is given in (transparency 17). Similar relations hold for the interaction of other hadrons with air at comparable energies. More details may be found in Ref. [8].

The largest influence on the longitudinal development of showers has - besides the inelastic cross sections - the 'inelasticity'. The average energy fraction of the highest energy baryon - which might be a definition of the elasticity (the inverse of inelasticity) - emerging from p-^{14}N collisions is shown in (transparency 18).

In the comparison of Ref. [8, 9] identical cross-sections have been used for all models. Recently a set of showers has been simulated using individual sets of cross-sections for each model [16].

4 Results of EAS simulations

What experiments never will be able to show is available in shower simulations: To plot the detailed EAS development, as given for γ, proton and Iron primaries at $E_0 = 10^{14}\ eV$ (vertical, VENUS model) in (transparency 19). Longitudinal and lateral distributions of different particle species are given in (transparencies 20 and 21). How the individual cross sections and inelasticities influence the longitudinal development may be seen in (transparency 22) (primary protons at vertical incidence) and (transparency 24) (primary Iron nuclei at vertical incidence). Both figures show the average on 500 showers of each species. The scatter of the electron number at detector level is given in (transparency 23) (proton primary) and (transparency 25) (Iron primary). The contours of a scatter plot of individual $log(N_e)/log(N_\mu)$ pairs are shown in (transparency 26), which indicates the possibility to discriminate between primary energy and primary mass.

5 Comparison: CORSIKA and AIRES

As SIBYLL is also linked with the air shower simulation program AIRES [24] (its version 1.2.0 is a Fortran transcription of the Pascal program MOCCA [25]) the influence of the embedding EAS code may be studied. Therefore data obtained with AIRES/SIBYLL [26] have been added to (transparency 27) (muon energy spectra for primary protons) and to (transparency 28) (muon lateral distributions for primary protons). The striking differences are i) the reduced number of muons at $E_\mu < 2\ GeV$, as shown in (transparency 27), and ii) the narrower lateral distribution especially at large distances $> 200\ m$ from the shower axis, which clearly is visible in (transparency 28). Both effects are due to the differing muon tracking in AIRES and CORSIKA. The resulting $log(N_e)$ vs. $log(N_\mu)$ plot is given in (transparency 29) with the AIRES areas hatched.

6 Muon component of EAS

The main source of muons in EAS are the decays of the $\pi^\pm$- and $K^\pm$-mesons, less important are the K_L^0-decays with their small branching ratio (transparency 30). An essential feature of these meson decays is their concurrence with hadronic interactions with air. The lines given in (transparency 31) represent equal chances for decay and interaction as function of meson energy and atmospheric depth. Therefore $\pi^\pm$- and K-decays predominantly contribute to the low energy muon spectrum below 100 - 1000 GeV. Minor sources of muons are i) the direct pair formation by high energy gammas and ii) the decay of charmed mesons. Despite the small cross-section for the $\gamma \rightarrow \mu^+\mu^-$ in the 10 $\mu barn$ range the importance of this generation mechanism comes from the energetic muons as the gamma energy is distributed only onto 2 muons. Similarly in the decay of rare charmed particles the energy is fully transferred to the $\mu^+\mu^-$-pair.

The influence of hadronic inelastic cross-sections on the development of EAS – higher cross-sections lead to a faster evolution at higher altitudes – extends also to the number and energy of muons arriving at sea level: An EAS development at higher altitudes favors the decay of pions to muons at expense of the $\pi^\pm$-interactions. Those muons originating from pions which stem from early interactions trend to a harder energy spectrum.

The three models based on Gribov-Regge theory differ only slightly in the number of charged pions originating from collisions of protons on Nitrogen, see Ref. [8]. In the momentum range up to $\approx 10^5\ GeV/c$ their hadron-air cross-sections exhibit a rather similar behavior, as shown in (transparency 12). The combination of both features leads to a similar shape of the muon energy spectrum (transparency 32) (proton primary). The slightly wider muon lateral distribution of DPMJET (transparency 33) (proton primary, all muons $> 0.3\ GeV$) is mainly due to the highest cross-section, which causes a faster development of the EAS at higher altitudes revealing a larger age parameter at ground level. The strong energy dependence of the lateral distribution is demonstrated by (transparency 34) (muons $> 80\ GeV$) and (transparency 35) (muons $> 1\ TeV$). In (transparency 36) the muons of 500 showers simulated with the QGSJET model (proton primary, $E_0 = 10^{15}\ eV$, vertical) are binned in the logarithmic scales of radial distance and muon energy. This distribution has a broad maximum between 10 m and 300 m rsp. 0.3 GeV and 100 GeV. More insight may give the contour plot of (transparency 37), showing the same data now representing the density per m^2. The influence of the different interaction models onto the

energy	model	average number of muons/shower above threshold energy				
		$> 0.3\ GeV$	$> 1\ GeV$	$> 10\ GeV$	$> 100\ GeV$	$> 1\ TeV$
$10^{14}\ eV$	VENUS	1354	1150	351	23.5	0.618
	QGSJET	1169	1008	310	20.9	0.696
	SIBYLL	1045	886	272	18.6	0.610
	HDPM	1487	1255	354	21.4	0.468
	DPMJET	1256	1073	322	21.4	0.590
$10^{15}\ eV$	VENUS	11618	9644	2699	155.4	3.702
	QGSJET	9577	8059	2257	129.8	3.332
	SIBYLL	7921	6531	1811	107.6	3.256
	HDPM	12370	10138	2545	133.2	3.030
	DPMJET	10534	8790	2400	133.6	3.440

Table 1: Average numbers of muons above threshold energy in vertical proton induced showers.

muon numbers with $E_\mu > 0.3\ GeV$ including their shower-to shower fluctuation is shown in (transparency 38) (proton primary, vertical incidence).

A recent revision of the QGSJET model parameters (not included in the data presented here) causes a slightly steeper increase of the hadron-air cross-sections, and thus a slight shift of the values of Table 1 towards larger numbers is obtained for this model (about 5% for $E_\mu > 100\ GeV$ at $10^{15}\ eV$).

7 Conclusion

Most of the processes which are modeled within the air shower simulation code CORSIKA are well understood, such as the electromagnetic processes or the particle decays; accelerator and collider experiments revealed many results which give a reliable basement for the description of low energy hadronic interactions (transparency 39). The largest uncertainties come from the hadronic interaction models when extrapolating to energies beyond those attainable by man-made accelerators. Comparing the EAS results simulated by the various interaction models, but all embedded in the identical environment of the CORSIKA code, significant differences show up. These differences give an impression of the influence on the EAS development. For some of the models (VENUS, QGSJET) we observe a fairly well agreement of simulations with experimental data [1] up to primary energies of $\approx 10^{16}\ eV$. Thus the muonic component of EAS simulations with muon energies exceeding about 70 GeV may be predicted with uncertainties

≤ 20 %.

Nevertheless a further evolution of CORSIKA will be necessary to improve its flexibility and universality as tool. This includes a replacement of the low energy hadronic interaction model which no longer satisfies the higher demands of today's simulation programs.

The advent of an improved version of the SIBYLL hadronic interaction model is announced [27]. It is intended to make this program available with CORSIKA in near future.

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