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Comparisons of measured and simulated energy spectra of electromagnetic particles at the Pamir emulsion experiment

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Abstract. The reconstructed energy spectrum of electromagnetic particles, measured at high-altitude is compared with spectra obtained by Monte Carlo simulations. The extensive air shower simulations are based on the CORSIKA program including different high energy interaction models, e.g. QGSJET, VENUS or neXus. Additionally the Monte Carlo includes a detailed simulation of the detector response for the particles based on the GEANT code. From the obtained optical density the energy of the particles is reconstructed with the same algorithms like at the Pamir experiment. These procedures enables to discuss in details resolution and threshold effects of the Pamir emulsion calorimeter at both, the optical density and the energy of the electromagnetic particles.

1 Introduction

Experiments at high mountain altitudes on Pamir or Mt. Chacaltaya measure electrons, gammas and hadrons with high particle energy thresholds in the TeV region by emulsions or X-ray films (Baradzei et al.,1992). Besides the reconstruction of the cores of extensive air-showers in the knee region by the so called particle families, integral measurements of single hadrons and electrons/gammas are performed. At high altitudes these particles stem mainly from primary cosmic rays of energies below 1 PeV and were produced in extremely forward direction. This explains the special suitability of these measurements for comparisons with expectations by high-energy hadronic interaction models: in the primary energy region of 10-100 TeV the elemental composition and flux of the cosmic rays are approximately known from direct measurements on balloons or satellites. The sensitivity of the emulsion experiments to the extreme forward direction of the interaction has complementary information to the data of accelerator experiments to which the cross sections of the interaction models are adjusted. Hence the measurement can be used for a test of these models (Haungs et al., 2001).

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In the present paper we compare the expected inclusive flux of e/γ for the Pamir experiment for seven different high-energy interaction models, all embedded in the air-shower simulation program CORSIKA (Heck et al., 1998). The measured distribution of the electromagnetic component with the e/γ-block of the Pamir experiment is compared with the expectations of the simulations including detailed detector simulations. The considered observable is the so-called optical density of spots displayed in X-ray films. The optical densities are then converted into the energy of the secondary particles and the resulting "reconstructed" spectra are discussed. Finally the results are compared with a measured spectrum: $I(>E) = (1.63 \pm 0.13) \cdot 10^{-6} \cdot (E/5TeV)^{-1.93 \pm 0.12}$ [$m^{-2}s^{-1}sr^{-1}$] (Bialawska, 1999).

2 CORSIKA air shower simulations

Air-shower events are generated for three different nuclei (H, He, Fe), using seven different interaction model codes: VENUS vers.4.12 (Werner, 1993), QGSJET vers. of CORSIKA 5.62 (Kalmykov et al., 1997), SIBYLL vers.1.6 (Engel et al., 1992), HDPM (Heck et al., 1998), DPMJET vers.2.4 (Ranft, 1995), SIBYLL vers.2.1 (Engel, 1999), and neXus vers.2β (Drescher et al., 1999), implemented in CORSIKA (basically vers. 5.62). For each primary and model 500,000 events were generated, except for the DPMJET and neXus models, where somewhat fewer events were simulated in view of the long computing time required for these codes. In the case of primary protons the simulations cover the energy range of 10^{13} eV - 10^{16} eV with slope $\gamma_H = 2.75$ and isotropic incidence up to $40°$. In the case of primary helium (iron) the slope used is $\gamma_{He} = 2.62$ ($\gamma_{Fe} = 2.60$) in the energy range $2 \cdot 10^{13}$ eV - 10^{16} eV (10^{14} eV - 10^{16} eV). The slopes were taken from the compilation of direct measurements (Wiebel-Sooth et al., 1998). All secondary particles with energies larger than 1 TeV at the observation level of the Pamir experiment (4370 m) are taken into account.

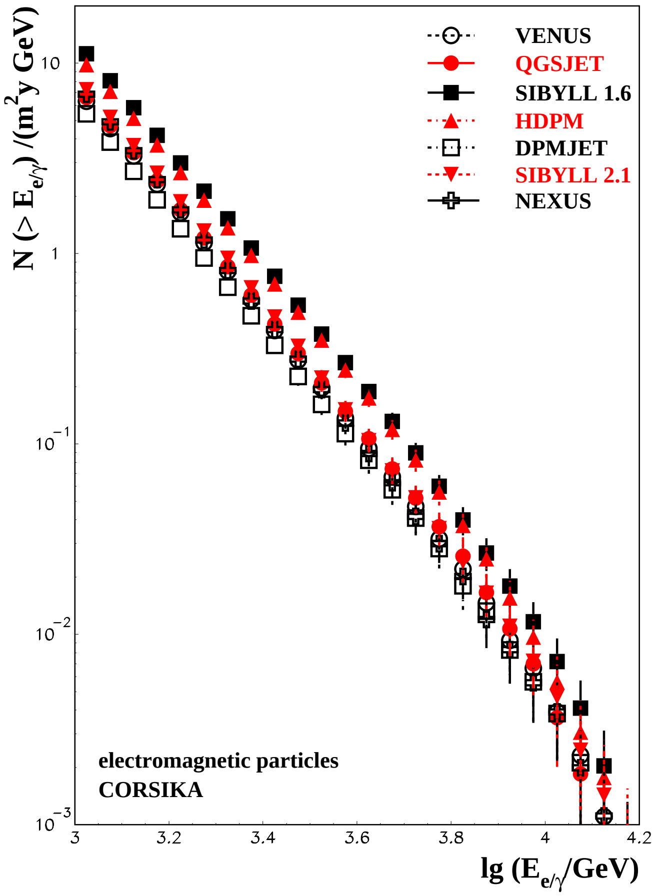

Fig. 1. The energy spectra of electromagnetic secondary shower particles above 1 TeV as expected for the Pamir observation level for different interaction models. The spectra are displayed in integral form and normalised to one m^2 and year. The error bars denote the statistical uncertainties of the simulations, which affect the high-energy tail of the spectra.

Figure 1 compares the integral energy spectra of electromagnetic particles for all interaction models. The spectra are reconstructed by the sum of the different progenitors weighted with the relative fluxes as estimated by a compilation of direct measurements (Wiebel-Sooth et al., 1998). It could be shown (Haungs et al., 1999, 1998) that heavy primaries give a nonsignificant contribution to such integral measurements. The contribution of heavy primaries is not only reduced owing to the assumed fluxes, but also by the faster development by showers induced by heavy particles. Primaries with larger energies do not compensate for this effect, due to the steeply decreasing primary spectrum.
Obviously the spectra shown in Figure 1 reflect somehow the primary energy spectra with their power law distribution. Above 10 TeV the spectra show a cut-off which is due to the missing ultra-high primary energies above 10^{16} eV at the simulations. The differences between the slopes from the different models are within statistical uncertainties, but the absolute scales of the predictions differ by a factor of 2-2.5. With a fit of a power law in the energy region 1–10 TeV we calculate the slope and the expected flux of particles above 5 TeV. The results are listed in Table 1. The SIBYLL 1.6 and HDPM produce significantly more and DPMJET significantly fewer particles than the other models. (This also holds for the hadronic secondary particles, see Haungs et al., 2000.)

Table 1. Fit results for the integral spectra of electromagnetic particles for different interaction models. The values are the parameters of the functional form $I(>E) = c \cdot (E/5TeV)^{\gamma}\,\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. The statistical errors of the parameters are in the order of 5-10%.

	coefficient c	slope γ
VENUS	$1.42 \cdot 10^{-6}$	-1.94
QGSJET	$1.57 \cdot 10^{-6}$	-1.93
SIBYLL 1.6	$2.72 \cdot 10^{-6}$	-1.87
HDPM	$2.50 \cdot 10^{-6}$	-1.83
DPMJET	$1.24 \cdot 10^{-6}$	-2.02
NEXUS	$1.26 \cdot 10^{-6}$	-2.05
SIBYLL 2.1	$1.57 \cdot 10^{-6}$	-1.95

3 Detector response

For electromagnetic particles the optical densities in the X-ray films were calculated for photons and electrons of different energies and angles of incidence by a detailed detector simulation using the GEANT tool (Haungs and Kempa, 1997). The optical density is the energy measure of such experiments. The results were then parameterised. An optical density is then calculated for each e.m. particle (of the CORSIKA simulations) with given energy and angle of incidence by interpolating the density distributions (Haungs and Kempa, 1998). These procedures account for the response of the detector, including its fluctuations, and for the efficiency and threshold effects of the Pamir experiment.
Figure 2 compares the expected density distribution for different interaction models with a typical data set of the Pamir experiment (Bialobrzeska et al., 1998). Above the large threshold region (the Pamir collaboration quote the threshold to be $\approx 4\,$TeV) a power law distribution is given. Again deviations from the power law behaviour is seen at high energies (large optical densities) due to the missing simulations for primary energies above 10^{16} eV. The behaviour and slope of the simulated distributions closely agree with the measurements, but the differences between the models in the absolute flux still hold. The differences in particle numbers as discussed for Fig. 1 are still evident after the detector simulation and conversion into the measured observable. That means the SIBYLL (version 1.6) and HDPM models predict the largest numbers and their particle fluxes are far off the measurements (note the integral form of the displayed spectra). They seems to produce too many electromagnetic particles above TeV energies at the observation level of Pamir. All the other models agree with the data within the statistical uncertainties of simulations and measurements. The DPMJET

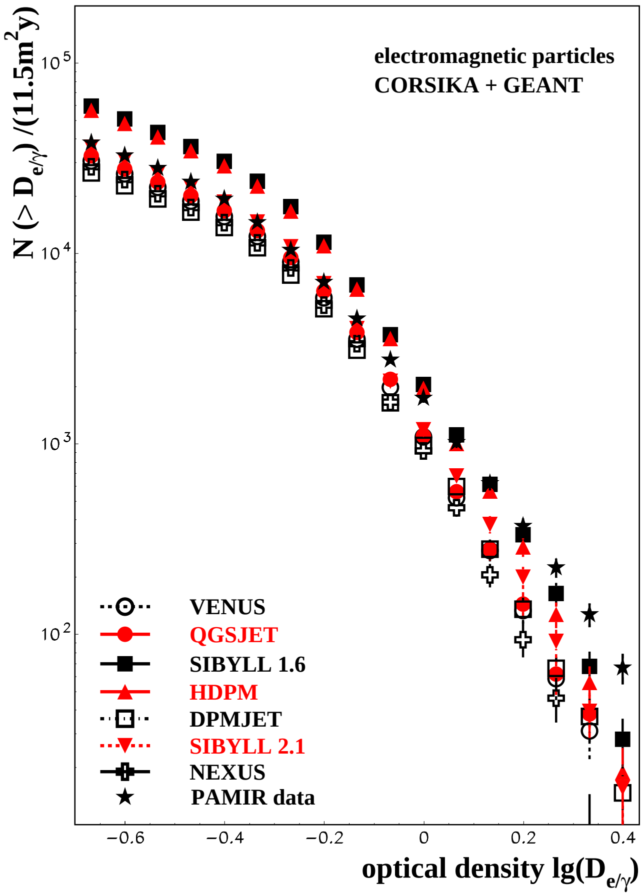

Fig. 2. The integral spectra of the optical density as expected for the Pamir observation level for different interaction models and for a typical data set of the Pamir experiment.

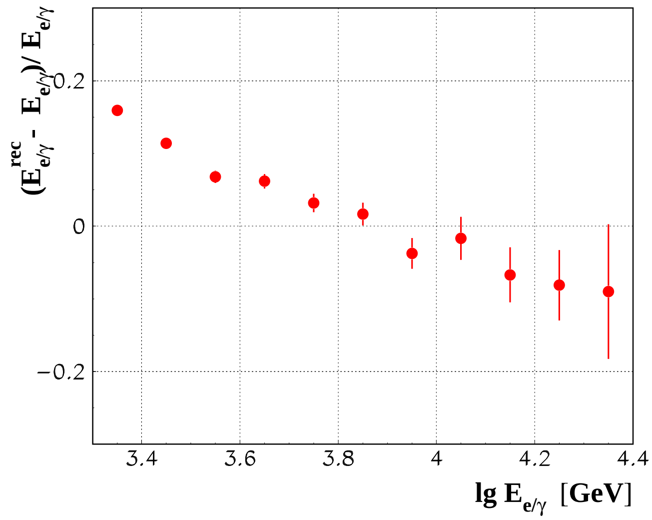

Fig. 3. The energy resolution of the reconstruction procedures of the Pamir experiment for electromagnetic secondary shower particles.

model tends to underestimate the total number of particles. In general the QGSJET and VENUS simulations match the data satisfactorily. This is confirmed by using various measured data samples of the same observable for the comparisons.

4 Energy reconstruction

After the simulation of the optical density the primary energy of the single particle can be reconstructed using the reconstruction procedures of the Pamir experiment. For each particle the energy is reconstructed from the optical density for the $r = 48\,\mu$m diaphragm according to the functions of Roganova and Ivanenko 1987 including the zenith angle of the particle. Figure 3 shows the quality of the energy reconstruction of this procedure for all particles with an integral optical density larger than 0.2. In spite of the high fluctuations in average the reconstruction quality is quite good with a relative error of less than 20% and nearly independent of the species of the particle (gamma or electron), but the resolution is energy dependent. At low energies near the threshold the reconstructed energy is larger than the true one. This could be due to systematic effects at the threshold of the Pamir experiment which may not be included in the calibration procedure. At energies above 10 TeV a tendency to an underestimation of the energy is obvious.

Figure 4 shows the reconstructed energy spectra for different interaction models as expected for the Pamir experiment including the detector response and the reconstruction procedures. The influence of the detection efficiency and threshold effects are visible up to 5 TeV. Again, for energies above 10 TeV the limited Monte Carlo statistics especially for ultra-high primary energies are affecting the spectra. The small energy region and poor statistics does not allow a power law fit to the reconstructed spectra. But the general features of the different interaction models still persist: the expected slopes are not very different, but the total flux varies for the different interaction models more than the uncertainty of the measurements. Nevertheless the reconstructed energy spectra reproduce the initial spectra (i.e. obtained by pure air-shower simulation without detector response and reconstruction efficiencies, Fig. 1) surprisingly well in the energy region between 5 and 10 TeV. A direct comparison in the case of the QGSJET model is shown in Figure 5. Therefore the slope and flux values of the initial spectra (see Table 1) can be compared with the measured energy spectrum (Bialawska, 1999):
$I(> E) = (1.63 \pm 0.13) \cdot 10^{-6} \cdot (E/5TeV)^{-1.93\pm0.12}$
given in [$\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$].

The hadronic interaction models VENUS, SIBYLL 2.1, and QGSJET show the best agreement with the measurements. All models reproduce the slope of the integral spectrum within the statistical uncertainty of the measurements, but for the expected flux for particles above 5 TeV some of the models deviate by a factor which is much larger than the uncertainties.

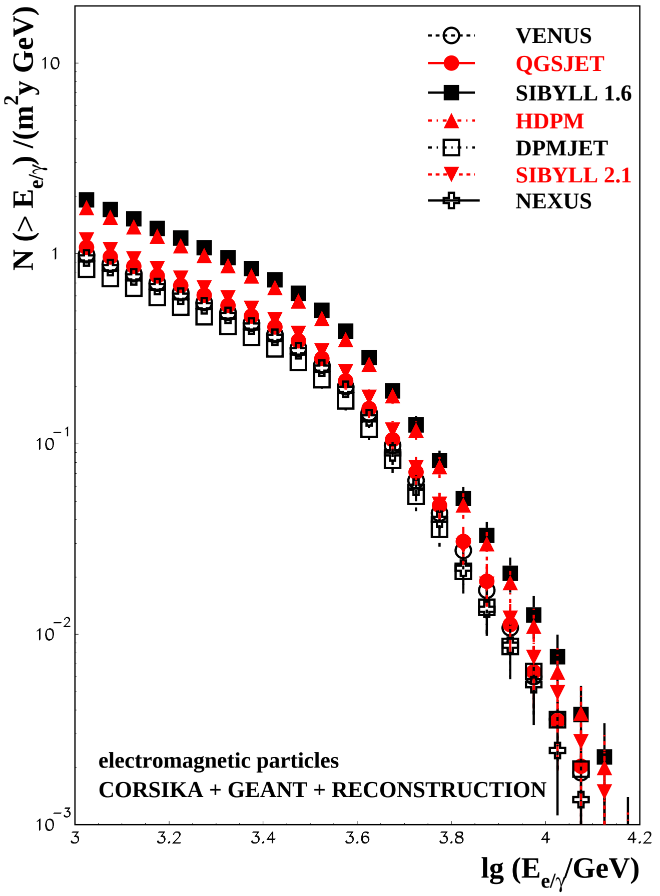

Fig. 4. The energy spectra of electromagnetic secondary shower particles including detector response and reconstruction procedures as expected for the Pamir observation level for different interaction models. The spectra are displayed in integral form and normalised to the measurement of one m^2 and year.

5 Conclusions

The combination of the air shower simulation in the atmosphere (CORSIKA with different high-energy interaction models) and the simulation of the detector response (GEANT) leads to a reasonable reconstruction of the measured energy spectrum of secondary electromagnetic particles. In spite of the excellent agreement of the measurements with expectations using QGSJET or VENUS as high-energy interaction models, the other models cannot be ruled out in general due to the large systematic uncertainties of the analyses. Main sources of systematic effects are the correction of hadronic particles producing spots in the emulsion chambers, which was accounted for up to 20%, and the uncertainty of the chemical composition of the cosmic rays, which is of the same order. Nevertheless the present investigations show a reasonable understanding of the detector response and reconstruction procedures of the Pamir emulsion experiment. Additionally the present results can be used as hints for the interpretation of the various interaction features in the models, especially for the extremely forward direction at relatively low primary energies of 50-1000 TeV.

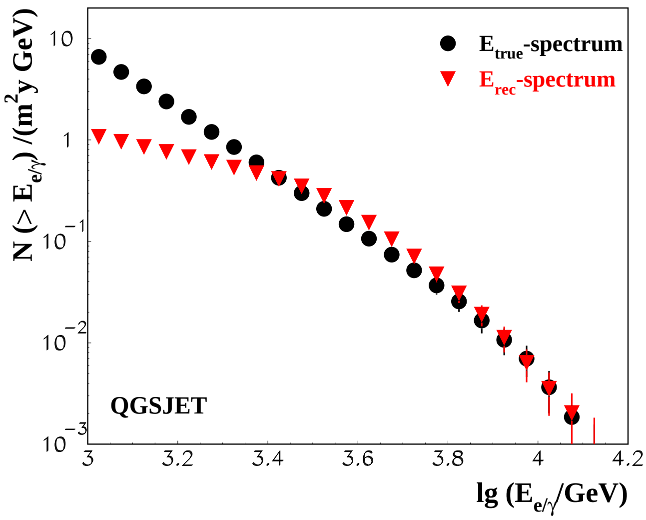

Fig. 5. The energy spectra of electromagnetic secondary shower particles as expected for the Pamir observation level with the interaction model QGSJET. The spectra are displayed in integral form and normalised to the measurement of one m^2 and year for both, the expectation of the pure air-shower development (CORSIKA) and with including detector response and energy reconstruction.

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