29th International Cosmic Ray Conference Pune (2005) **7**, 103–106

Dependence of the longitudinal shower profile on the characteristics of hadronic multiparticle production

T. Pierog[a], M. Alekseeva[b], T. Bergmann[a], V. Chernatkin[c], R. Engel[a], D. Heck[a], N.N. Kalmykov[b], S. Ostapchenko[a], M. Unger[a] and K. Werner[c]

(a) Forschungszentrum Karlsruhe, Postfach 3640, D-76021 Karlsruhe, Germany
(b) Skobeltsyn Institute of Nuclear Physics, Moscow State University, Leninskie Gory 1, 119992, Moscow, Russia
(c) SUBATECH, Universite de Nantes, EMN, IN2P2/CNRS, Nantes, France
Presenter: R. Engel (Ralph.Engel@ik.fzk.de), ger-engel-R-abs2-he14-oral

The new hybrid simulation code CONEX is used to study longitudinal shower profiles and their dependence on the applied hadronic interaction model. In addition to the mean depth of shower maximum, we also investigate the model dependence of different estimators for the total shower energy. The large differences of model extrapolations to ultra-high energy are significantly reduced if the calorimetric energy of shower and energy deposit at shower maximum are considered.

1. Introduction

At shower energies above 10^{17} eV, the longitudinal shower profile can be determined from measurements of the fluorescence light signal produced in the atmosphere. The number of produced fluorescence photons is expected to be directly proportional to the ionization energy deposit of the shower particles. Therefore, the fluorescence technique allows not only the determination of the depth of shower maximum but also the direct measurement of the calorimetric energy of an air shower – the energy that is transferred to em. particles and finally converted to ionization energy. Traditionally, assuming a mean energy deposit per particle, measured fluorescence light profiles are converted to shower size curves that are then compared with theoretical predictions. However, it is much more natural to calculate and compare energy deposit profiles as they are first of all directly related to the number fluorescence photons and secondly do not depend on the simulation thresholds [1].

In this paper we use the hybrid cascade code CONEX [2] to simulate realistic energy deposit profiles of a large number of showers (about 1000 showers per energy value) to compare the predictions of different hadronic interaction models.

2. Shower depth of maximum

The mean depth of maximum of a hadron-induced shower is closely related to the description of high-energy hadron production. In Fig. 1 we compare the predictions obtained with CONEX for neXus 3.97 [3], QGSJET 01 [4], and Sibyll 2.1 [5]. GHEISHA 2002 [6] is used as low-energy model for interactions below 80 GeV lab. energy. All three high-energy interaction models differ significantly in their predictions. For example, in the case of Sibyll and QGSJET there are two counter-acting effects that nearly cancel each other. The cross section of Sibyll is much larger than that of QGSJET, leading to a higher first interaction point. At the same time the larger elasticity of Sibyll causes a shift the shower development deeper into the atmosphere. In the case of neXus and QGSJET the differences arise due mainly to the different secondary particle distributions. The cross section of neXus and QGSJET are very similar, however, neXus predicts more high-energy secondary pions.

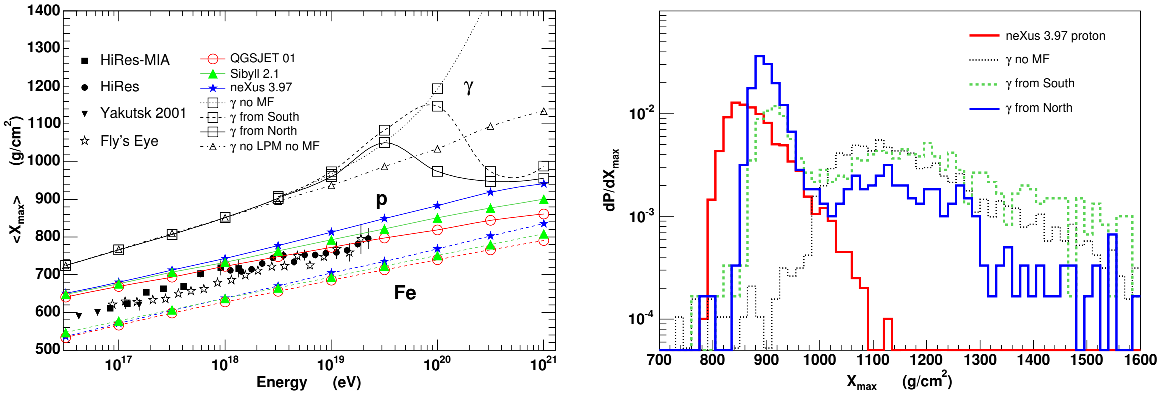

Figure 1. Left: mean depth of shower maximum of hadronic showers for three different interaction models. Also shown are photon-induced showers for different directions to the local geomagnetic field (MF). The references to the experimental data are given in [7]. Right: comparison of the distribution of the depth of maximum of photon- and proton-induced showers at 10^{20} eV.

The mean depth of maximum of photon-induced showers is strongly influenced by the Landau-Pomeranchuk-Migdal (LPM) effect and depends on the relative direction of the shower axis to the geomag. field. At high energy, photons can produce an em. shower already well above the atmosphere by interacting with the Earth's magnetic field. In Fig. 1 this is illustrated by showing the predictions for photon showers of 60° at the southern Auger detector coming from the north (weak mag. field effect) and from the south (strong mag. field effect). For reference, also calculations without mag. field and without both LPM effect and mag. field are shown.

As many exotic models for ultra-high energy cosmic rays predict a large fraction of photons at high energy, it is interesting to compare the $X_{\max}$ distributions of protons and photons. In Fig. 1 (right) these distributions are shown at 10^{20} eV. A significant fraction of photon showers (those that either pre-shower in the geomag. field or have a high-energy hadronic interaction in the early shower development) cannot be distinguished from proton showers on the basis of $X_{\max}$ only.

3. Primary energy estimation

The calorimetric energy of a shower, E_{cal}, is defined as the depth-integral of the ionization energy deposit profile. Integrating numerically the simulated profiles and accounting for muons and hadrons at large depth [8], we calculate the calorimetric energy of showers for a "perfect" measurement. In Fig. 2 (left) the correction factor $f = E_{\text{tot}}/E_{\text{cal}}$ is shown with which the calorimetric energy has to be multiplied to obtain the primary particle energy. The black lines are the mean conversion factors averaged over the predictions of all three models considered here and averaged over proton and iron primaries. The ratio of the total to calorimetric energy is directly related to the number of consecutive hadronic interactions (number of generations) that pions undergo before they decay. In each of these interactions about 1/3 of the secondary particles are neutral pions that transfer all of their energy to the electromagnetic shower component. Since the typical energy at which pions decay is about $100 - 200$ GeV, the number of generations increases with increasing primary energy. As the number of generations also influences the number of muons produced in a shower, there is a close relation between the number of muons and the calorimetric energy. Both the factor f and the predicted number of muons in high energy showers are bigger for QGSJET than Sibyll.

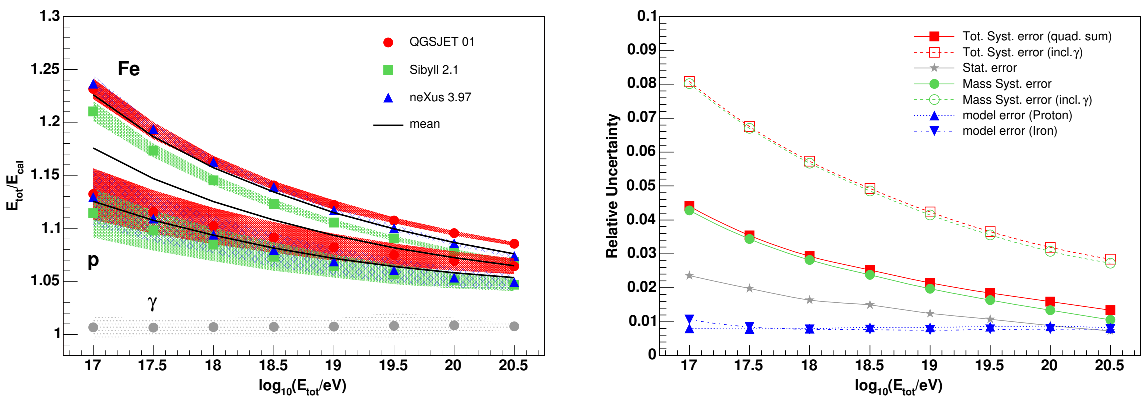

Figure 2. Left: mean value and RMS of the ratio of primary particle energy to calorimetric energy, shown for different models and primary particles. Right: relative uncertainty in energy reconstruction implied by the use of a conversion factor between the calorimetric and total energies that is averaged over models and primary particle types.

The uncertainty in reconstruction of the primary energy, assuming perfect calorimetric energy determination, is shown in Fig. 2 (right). We distinguish here between the statistical error due to shower-to-shower fluctuations and the systematic error due to differences implied by not knowing the cosmic ray composition and by different assumptions on hadronic interactions. The blue curves (triangles) show the systematic uncertainty one would have due to different interaction models if the composition were either only proton or only iron. The grey curve (stars) shows the statistical shower-to-shower uncertainty in total energy reconstruction, again assuming that the primary particle type is known. The green curve (filled circles) shows the systematic uncertainty if the composition is hadronic (in the range between proton and iron) but not known. It is calculated by applying the mean conversion factor f shown as the second black line in the l.h.s. figure. The red curve (filled squares) shows the total systematic error: the uncertainty due to the model dependence for a fixed composition is added quadratically to the uncertainty due to the unknown composition. If one considers the case of having a significant fraction of photons as primary particles, the curves with open symbols have to be used to estimate the uncertainties. They represent the composition-related and total systematic uncertainties if the conversion factor is calculated as average over proton, iron, and photon primaries.

The shower size at maximum is also well correlated with the primary energy and can be used as energy estimator. Motivated by the primary observable of fluorescence technique experiments, we show in Fig. 3 the factor by which the energy deposit at shower maximum has to be scaled to obtain the primary shower energy. Compared to the calorimetric energy, the energy deposit at shower maximum is subject to larger shower-to-shower fluctuations. On the other hand, the predictions are less model- and composition dependent over a wide energy range. In particular at about $10^{19.5}$ eV the conversion from the energy deposit to total energy is nearly independent of the primary particle type, including photons, and the assumed interaction model. Note the different behaviour of photon-induced showers due to the smaller muon number and the interplay between the LPM effect and mag. pre-showering.

The uncertainty in reconstruction of the total energy, again assuming perfect determination of the energy deposit at shower maximum, is shown in Fig. 3 (right). The labelling of the different curves is analogous to Fig. 2. The systematic uncertainty is very small at about $10^{19.5}$ eV.

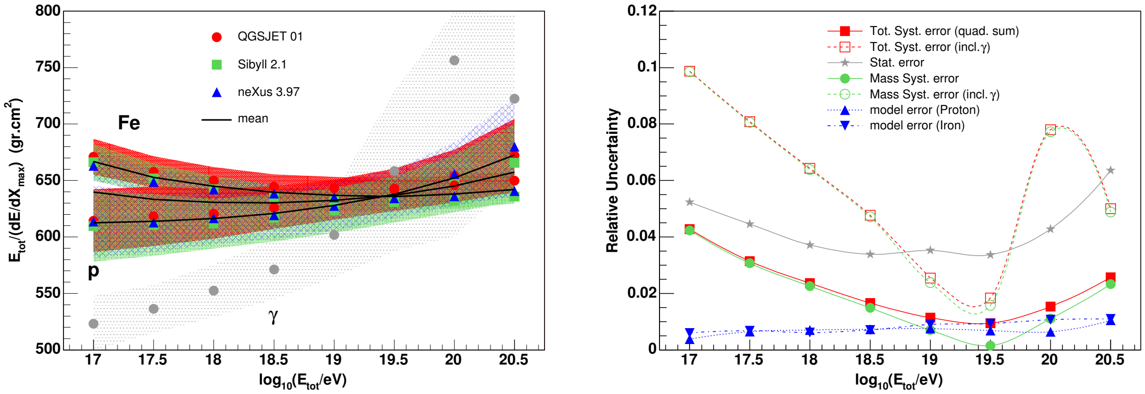

Figure 3. Left: mean ratio of total shower energy to the energy deposit at shower maximum. The shaded bands show the RMS of the shower-to-shower fluctuations. The black lines are the mean conversion factors averaged over the three models considered here and averaged over proton and iron primaries. Right: relative uncertainty in energy reconstruction implied by the use of energy deposit at shower maximum and a conversion factor that is averaged over models and primary particle types.

4. Conclusions and outlook

Differences in the extrapolation of the characteristics of had. interactions to ultra-high energy lead to a significant spread in the predictions of the mean depth of shower maximum. In contrast, the variation of the predictions on energy estimators such as the calorimetric energy and the energy deposit at shower maximum is relatively small. The total energy reconstruction uncertainty, assuming a perfect shower measurement, is dominated by the unknown primary composition. Using the calorimetric energy one obtains an uncertainty that is smaller than 4% for hadronic primaries in the energy range of relevance to current fluorescence detector experiments. The energy deposit at shower maximum can also be applied as independent energy estimator. Though being characterized by larger statistical fluctuations, it gives an almost model- and composition-independent measure of the primary energy at about 10^{19} eV.

References

[1] M. Risse and D. Heck, Astropart. Phys. 20 (2004) 661.
[2] M. Alekseeva et al., these proceedings, ger-ostapchenko-S-abs2-he14-poster; T. Pierog et al., astro-ph/0411260.
[3] H.J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, Phys. Rep. 350 (2001) 93 and hep-ph/0007198.
[4] N.N. Kalmykov, S. Ostapchenko, and A.I. Pavlov, Nucl. Phys. B (Proc. Suppl.) 52B (1997) 17 and Phys. At. Nucl. 56 (1993) (3) 346.
[5] R. Engel, T. K. Gaisser, P. Lipari, and T. Stanev, Proc. of 26th ICRC (Salt Lake City) vol. 1, p. 415, 1999; R. S. Fletcher, T. K. Gaisser, P. Lipari, and T. Stanev, Phys. Rev. D50 (1994) 5710.
[6] H. Fesefeldt, Report PITHA-85/02, RWTH Aachen, 1985.
[7] R. Engel and H. Klages, C. R. Physique 5 (2004) 505.
[8] H.M.J. Barbosa, F. Catalani, J.A. Chinellato, and C. Dobrigkeit, Astropart. Phys. 22 (2004) 159.