Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 4 (HE part 1), pages 625–628

ID 899

30th International Cosmic Ray Conference

Mérida, México

Latest Results of Air Shower Simulation Programs CORSIKA and CONEX

T. Pierog[1], R. Engel[1], D. Heck[1], S. Ostapchenko[1,2] and K. Werner[3].
[1] *Forschungszentrum Karlsruhe, Institut für Kernphysik, Karlsruhe, Germany*
[2] *D.V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia*
[3] *SUBATECH, University of Nantes – IN2P3/CNRS– EMN, Nantes, France*
pierog@ik.fzk.de

Abstract: Interpretation of EAS measurements strongly depends on detailed air shower simulations. The uncertainty in the prediction of shower observables for different primary particles and energies is currently dominated by differences between hadronic interaction models. The new models QGSJET II-3 and EPOS 1.6, which reproduce all major results of existing accelerator data (including detailed data of RHIC experiments for EPOS), have been implemented in the air shower simulation programs CORSIKA and CONEX. We show predictions of these new models and compare them with those from older models such as QGSJET01 or SIBYLL. Results for important air shower observables are discussed in detail.

Introduction

The experimental method of studying ultra-high energy cosmic rays is an indirect one. Typically, one investigates various characteristics of extensive air showers (EAS), a huge nuclear-electromagnetic cascade induced by a primary particle in the atmosphere, and uses the obtained information to infer the properties of the original particle, its energy, type, direction etc. Hence, the reliability of ultra-high energy cosmic ray analyses depends on the use of proper theoretical and phenomenological descriptions of the cascade processes.

The most natural way to predict atmospheric particle cascading in detail seems to be a direct Monte Carlo (MC) simulation of EAS development, like it is done, for example, in the CORSIKA program [1]. As a very large computation time is required at high energy, an alternative procedure was developed to describe EAS development numerically, based on the solution of the corresponding cascade equations. Combining this with an explicit MC simulation of the most energetic part of an air shower allows us to obtain accurate results both for average EAS characteristics and for their fluctuations in CONEX program [2].

After briefly describing recent changes introduced in CORSIKA and CONEX, we will present the latest results for important air shower observables obtained with these models.

Improvements of CORSIKA and CONEX

Last year QGSJET II-3 [3] and this year EPOS 1.6 [4] have been introduced in both CORSIKA and CONEX as new hadronic interaction models. These models have quite different philosophies. The first one is dedicated to cosmic ray physics and based on the re-summation of enhanced pomeron graphs to all orders [5]. The latter one is designed for high energy physics and partially relies on a more phenomenological approach, aiming at a nearly perfect description of accelerator data, in particular new RHIC measurements. Some results are presented in the following (see also [6]).

Concerning the particle tracking algorithms, the most important improvement in the last release of CORSIKA (6.611) is the possibility to combine the SLANT/UPWARD/CURVED options [7] in order to simulate air showers with any kind of zenith angle, including upward going showers (from 0° to 180°). The calculation of slant depth distances has been improved using the work of [8] as also employed in CONEX. In Fig. 1 the mean longitudinal

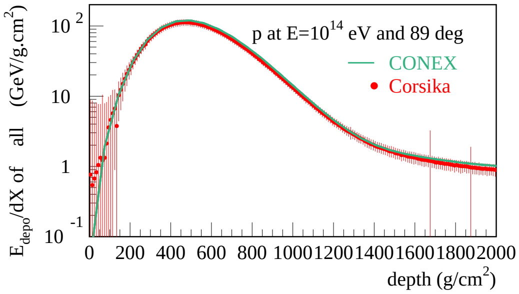

Figure 1: Mean longitudinal energy deposit profile in GeV $\mathrm{g}^{-1}\,\mathrm{cm}^2$ as a function of the slant depth in g cm^{-2} for proton induced 89° inclined showers at 10^{14} eV simulated with CORSIKA (red dots) and CONEX (green line) using QGSJET01.

energy deposit profile is shown as a function of the slant depth for proton induced showers of 89° at 10^{14} eV, simulated with CORSIKA and CONEX using QGSJET01 [9]. Even for this extreme zenith angle, very good agreement between the two programs is found.

Furthermore, in order to improve muon propagation, the Sternheimer density correction of the ionization energy loss has been extended to apply also to muons in both CORSIKA and CONEX, based on work by Kokoulin & Bogdanov [10]. The effect of the density correction can be seen in Fig. 2.

A major technical improvement was achieved in CORSIKA by replacing the old version manager CMZ by the combination of AUTOCONF/AUTOMAKE tools for the installation and selection of options in CORSIKA. Compilation has not to be done by the user anymore, rather Makefiles are generated by AUTOMAKE. Options are selected by a shell script using AUTOCONF and standard C preprocessor commands in the CORSIKA source code.

Finally, the interfaces to FLUKA 2006.3 [11] and HERWIG 6.51 [12] have been updated.

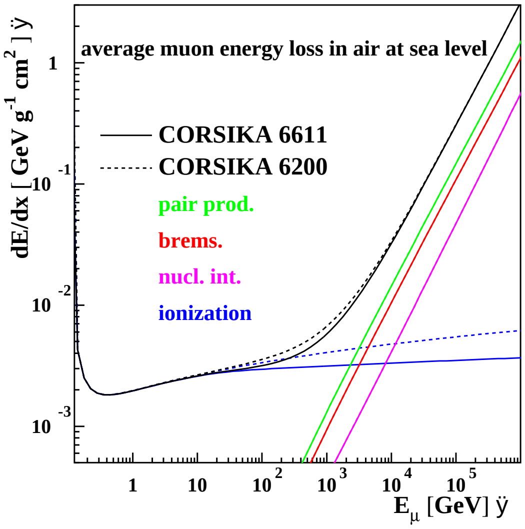

Figure 2: Muon energy loss in GeV $\mathrm{g}^{-1}\,\mathrm{cm}^2$ as function of total muon energy in GeV for CORSIKA versions 6.200 (dashed) and 6.611 (full).

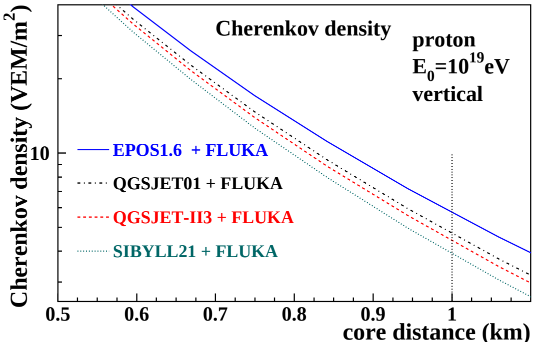

Figure 3: Mean lateral distribution function of Cherenkov density for 10^{19} eV vertical proton induced showers and different high-energy hadronic interaction models, EPOS 1.6 (full), QGSJET01 (dashed-dotted), QGSJET II-3 (dashed) and SIBYLL 2.1 (dotted).

Latest results

In the following air shower simulation results using EPOS 1.6 and QGSJET II-3 are presented and compared to former results using QGSJET01 [9] or SIBYLL 2.1 [13, 14].

In Fig. 3, CORSIKA-based estimates for the lateral distribution of the Cherenkov signal in Auger tanks [15] are shown. The tank signal has been simulated in a simplified way as only the relative differences between the model results are of importance here. Due to a much larger muon number at ground in EPOS [6, 16], the density at 1 km shows an excess of about 30 to 40% compared to QGSJET II-3 while the latter is well in between QGSJET01 and SIBYLL. Such an excess is of crucial importance for the reconstruction of the primary energy and composition with the Auger surface detector alone [17]. Compared to other models, using EPOS would decrease the energy reconstructed from lateral densities and could lead to a lighter primary cosmic ray composition.

The higher muon number from EPOS is mainly due to a larger baryon-antibaryon pair production rate in the individual hadronic interactions in showers. By predicting more baryons, more energy is kept in the hadronic shower component even at low energy. As a consequence, the calorimetric energy as measured by fluorescence light detectors is reduced since more energy is transferred to neutrinos and muons. In Fig. 4 the conversion factor from the visible calorimetric energy to the real energy is plotted as a function of the primary energy of the showers. QGSJET II-3 gives results very similar to SIBYLL. As expected, EPOS shows a conversion factor which is up to 3.5% higher than other models at low energy.

As shown in Fig. 5, the mean depth of shower maximum, $\mathrm{X}_{\mathrm{max}}$, for proton and iron induced showers simulated with CONEX is nevertheless not very different for EPOS. Up to 10^{19} eV, all models agree within $20\mathrm{g}\ \mathrm{cm}^{-2}$. EPOS proton induced showers show a slightly higher elongation rate in that range while QGSJET II-3 has a slightly lower one. Above this energy, both QGSJET01 and QGSJET II-3 elongation rates decrease due to the very large multiplicity of these models at ultra-high energy. Below 10^{18} eV, an analysis of X_{max} data would lead to a composition of primary cosmic rays that is heavier using QGSJET II-3 compared to EPOS. Above 10^{18} eV the situation is reversed.

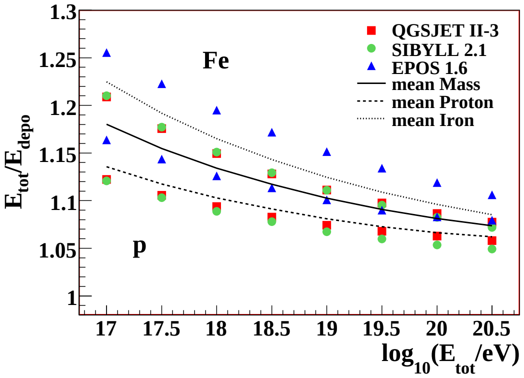

Figure 4: Mean factor for the conversion of observed (calorimetric) energy to total energy for iron (dotted) or proton (dashed) induced showers. The conversion factor is shown for QGSJET II-3 (circles), SIBYLL 2.1 (squares) and EPOS 1.6 (triangles). The mean conversion factor (full line) is calculated by averaging all proton and iron predictions.

Conclusions

New versions of CORSIKA and CONEX have been released recently with two new hadronic interaction models. The models differ in several important aspects in the approach of reproducing data. In QGSJET II-3, high parton density effects are treated by re-summing enhanced pomeron graphs to all orders, but energy conservation at amplitude level is not implemented. On the other hand, in EPOS, energy conservation at amplitude level is fully implemented, but high-density effects are treated by a phenomenological parametrization. EPOS is particularly well-tuned to describe available accelerator data including heavy ion collisions measured at RHIC. The differences of the model predictions are large: At high energy, proton induced air showers simulated with EPOS have even more muons at ground than iron induced showers simulated with QGSJET II-3. Comparison to cosmic ray data, for example, from the KASCADE

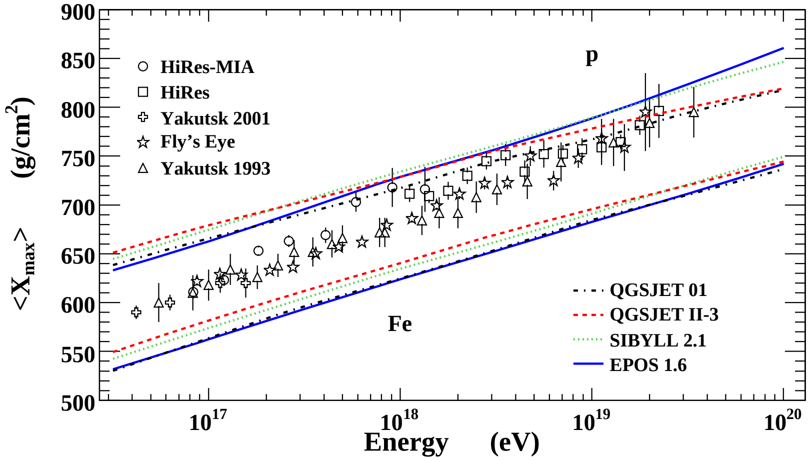

Figure 5: Mean $X_{\max}$ for proton and iron induced showers as a function of the primary energy. Predictions of different high-energy hadronic interaction models, QGSJET01 (dashed-dotted), QGSJET II-3 (dashed), SIBYLL 2.1 (dotted) and EPOS 1.6 (full), are compared to data. Refs. to the data can be found in [18]

detector, are now needed to support or disfavour the EPOS predictions [19].

Acknowledgments: The CORSIKA and CONEX authors would like to thank all users who contributed to the development of the programs by helping to detect and solve problems. We are particularly grateful to R.P. Kokoulin and A.G. Bogdanov for their very useful work and comments on muon interactions and energy loss.

References

[1] D. Heck *et al.*, Wissenschaftliche Berichte FZKA 6019, Forschungszentrum Karlsruhe, 1998.

[2] T. Bergmann *et al.*, Astropart. Phys. 26 (2007) 420–432 and astro-ph/0606564.

[3] S. Ostapchenko, Phys. Rev. D74 (2006) 014026 and hep-ph/0505259.

[4] K. Werner *et al.*, Phys. Rev. C74 (2006) 044902 and hep-ph/0506232.

[5] S. Ostapchenko, Phys. Lett. B636 (2006) 40–45 and hep-ph/0602139.

[6] T. Pierog and K. Werner, These proceedings #0905 (2007) .

[7] D. Heck, Wissenschaftliche Berichte FZKA 7254, Forschungszentrum Karlsruhe, 2006.

[8] V. Chernatkin, *Simulation des gerbes dues aux rayons cosmiques a très hautes énergies* PhD thesis Université de Nantes 2005.

[9] N. N. Kalmykov, S. S. Ostapchenko, and A. I. Pavlov, Nucl. Phys. Proc. Suppl. 52B (1997) 17–28.

[10] R. P. Kokoulin and A. G. Bogdanov, 2007 private communication.

[11] A. Ferrari *et al.*, CERN-2005-010.

[12] G. Corcella *et al.*, hep-ph/0210213, 2002.

[13] R. S. Fletcher, T. K. Gaisser, P. Lipari, and T. Stanev, Phys. Rev. D50 (1994) 5710–5731.

[14] R. Engel, T. K. Gaisser, P. Lipari, and T. Stanev, in Proceedings of 26th ICRC (Salt Lake City) vol. 1, p. 415, 1999.

[15] J. Abraham *et al.* (Pierre Auger Collab.), Nucl. Instrum. Meth. A523 (2004) 50–95.

[16] T. Pierog and K. Werner, astro-ph/0611311, 2006.

[17] R. Engel *et al.* (Pierre Auger Collab.), These proceedings #0605 (2007) .

[18] R. Engel and H. Klages, Comptes Rendus Physique 5 (2004) 505–518.

[19] H. Ulrich *et al.* (KASCADE-Grande Collab.), These proceedings #0178 (2007) .