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Hadronic interaction models and the air shower simulation program *CORSIKA*

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Abstract. The Monte Carlo program CORSIKA simulates the 4-dimensional evolution of extensive air showers in the atmosphere initiated by photons, hadrons or nuclei. It contains links to the hadronic interaction models DPMJET, HDPM, NEXUS, QGSJET, SIBYLL, and VENUS. These codes are employed to treat the hadronic interactions at energies above 80 GeV. Since their first implementation in 1996 the models DPMJET and SIBYLL have been revised to versions II.5 and 2.1, respectively. Also the treatment of diffractive interactions by QGSJET has been slightly modified. The models DPMJET, QGSJET and SIBYLL are able to simulate collisions even at the highest energies reaching up to 10^{20} eV, which are at the focus of present research. The recently added NEXUS 2 program uses a unified approach combining Gribov-Regge theory and perturbative QCD. This model is based on the universality hypothesis of the behavior of high-energy interactions and presently works up to 10^{17} eV. A comparison of simulations performed with different models gives an indication on the systematic uncertainties of simulated air shower properties, which arise from the extrapolations to energies, kinematic ranges, or projectile-target combinations not covered by man-made colliders. Results obtained with the most actual programs are presented.

1 Introduction

One of the reasons for the success of CORSIKA (**CO**smic **R**ay **SI**mulation for **KA**scade) (Heck et al., 1998) as the most-used air shower simulation program comes from the combination of the best programs available to describe the interactions of the various particles which appear in the development of Extensive Air Showers (EAS). E. g. the electromagnetic interactions of gammas, electrons and positrons are simulated by a tailor-made version of the Electron Gamma Shower code EGS4 (Nelson et al., 1985).

The largest uncertainties in numerical simulation of EAS with primary energies above some TeV are induced by the models which describe the hadronic interactions. Especially, when extrapolating to the highest energies, where the collision energies exceed those attainable with man-made accelerators, or to kinematic ranges not accessible with ordinary collider experiments one has to rely on theoretical guidelines to describe the interactions. Essential uncertainties stem from the fact that just those interaction products emitted at small angles into the extreme forward direction carry away the largest energy fraction, but in collider experiments those particles disappear in the beam pipe without being observable. In the development of EAS such particles are responsible for transporting the energy down into the atmosphere.

Six different hadronic interaction codes are presently coupled with the CORSIKA code: DPMJET (Ranft, 1995 & 1999), HDPM (Capdevielle et al., 1992; Heck et al., 1998), NEXUS (Drescher et al., 2000), QGSJET (Kalmykov et al., 1997), SIBYLL (Fletcher et al., 1994; Engel et al., 1999), and VENUS (Werner, 1993). These links offer the unique possibility to study how shower observables depend on different hadronic interaction models, thus deriving the systematic uncertainties of predictions from simulations.

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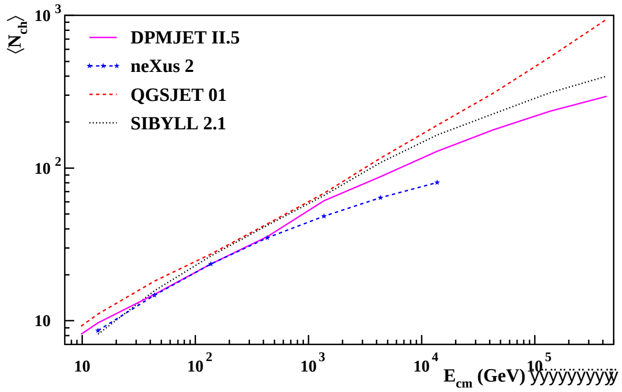

Fig. 1. Average charged particle multiplicity as function of energy for p-^{14}N-collisions.

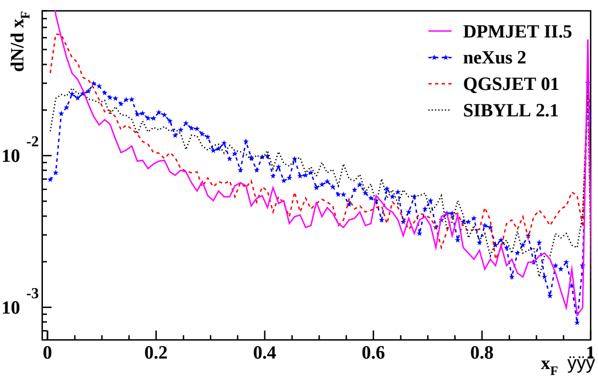

Fig. 2. Feynman-x distribution of most energetic baryon emerging from p-^{14}N-collisions at $E_{\mathrm{lab}} = 10^7$ GeV.

2 Updated and new models

Since our first comparison of hadronic interaction models (Knapp et al., 1996) most of these models are replaced by revised versions. With NEXUS a completely new designed code is now available for air shower simulations.

2.1 DPMJET upgrade

Besides technical improvements DPMJET is upgraded to version II.5 by including new Dual-Parton-Model diagrams which lead to an enhanced baryon stopping power (Ranft, 1999) in nucleon-nucleon and nucleon-nucleus interactions.

2.2 NEXUS 2 features

The NEXUS model (Drescher et al., 2000) starts from the universality hypothesis stating that *the mechanisms of high energy interactions are identical in different reactions*. Thus, one can study the final state (s-channel) parton evolution and the subsequent hadronization on the basis of the e^+e^--reaction data, while the data on deep inelastic lepton-proton scattering allow to test the model description of the initial (t-channel) parton cascade. Proceeding in this way the modeling of the complicated mechanism of hadronic interaction is decomposed into separate ‘building blocks’ which are deduced from simpler systems. Also, fixing the relevant model parameters on the basis of data on different reactions allows to restrict considerably the parameter freedom of the model approach and to assure a more reliable extrapolation of the model to higher energies.

By construction NEXUS is a unified Gribov-Regge model of soft and hard interactions. While the former are described in the traditional way by the phenomenological soft Pomeron exchanges (Werner, 1993), the latter are treated using the perturbative QCD techniques, within the concept of the ‘semi-hard Pomeron’. An important feature of NEXUS is the fully self-consistent treatment of the energy-momentum sharing between individual elementary scattering processes, including virtual rescatterings (Hladik et al., 2001). This is taken into account both in the cross-section calculations and in the particle production treatment. As demonstrated in Fig. 1 for p-^{14}N-interactions this leads to a rather moderate increase of the average charged particle multiplicity with energy.

2.3 QGSJET modifications

The modifications of QGSJET 01 concern a more correct treatment of diffractive processes in hadron-nucleus collisions. In the QGSJET treatment (quasi-eikonal approach), the diffraction acts essentially as a coherent process, which implies that the probability for *both* projectile and target diffraction should be calculated averaging over impact parameter of the interaction and over positions of the nucleons. In the previous version of the model the projectile diffraction had been simulated *after* sampling a particular impact parameter, thus violating to some extent the unitarity condition at small impact parameters. Now the diffraction processes are chosen according to the correct probability, without specifying a particular impact parameter in that case. On average the hadron-nucleus collisions show a slightly lower elasticity and the simulated EASs tend to a faster aging.

2.4 SIBYLL improvements

The old SIBYLL version 1.6 (Fletcher et al., 1994) is based on the minijet model and frequently used in combination with air-shower simulation programs like MOCCA (Hillas, 1997) or AIRES (Sciutto, 1999). Fundamental modifications (Engel et al., 1999) introduced the exchange of multiple soft Pomerons and an energy dependent transverse momentum cut-off of the minijets. These improvements revealed a considerably better agreement with experimental data. Though not released officially, for this analysis SIBYLL version 2.1 is used for comparisons. Further fine-tuning towards a settled version is ongoing (Engel, 2001).

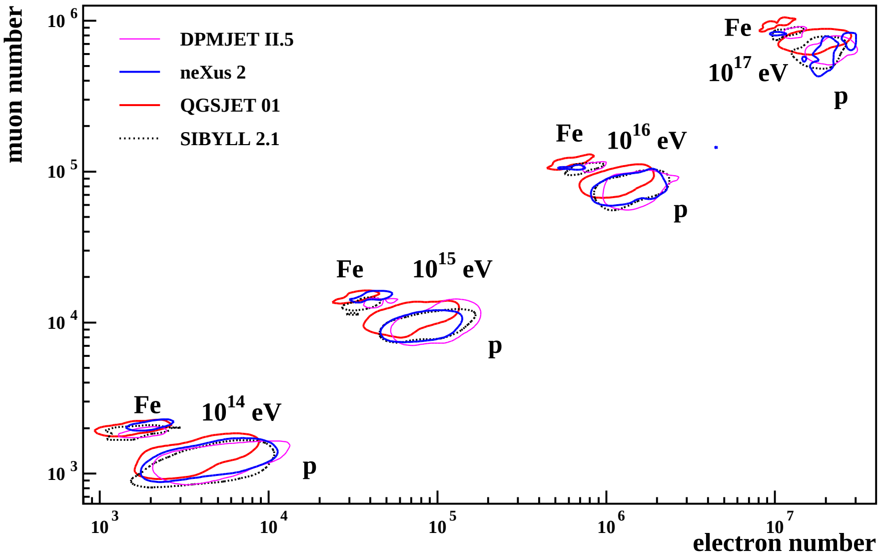

Fig. 3. Predicted number of muons vs. number of electrons at the KASCADE-Grande experiment (110 m a.s.l.) for vertical incident proton (p) and iron (Fe) primaries at various primary energies. The contour lines are drawn at half maximum of the respective two-dimensional distributions generated by 500 proton and 200 iron induced showers for each primary energy.

3 Comparison of actual models

^{14}N-nuclei are the most frequent targets of hadronic interactions in the EAS development, and therefore we compare such hadronic collisions. Fig. 2 shows the distribution of the longitudinal momentum fraction which is carried away by the most energetic baryon from p-^{14}N-collisions at E_{lab} = 10^{16} eV. For the development of EAS the most interesting portion is at $x_F > 0.8$ as particles in this range carry away the largest fraction of the collision energy, thus transporting the remainder of the projectile energy deeper into the atmosphere. But just in this range the different models exhibit larger differences. This plot should be compared with (Knapp, 1999) to see the improvements in the description of diffractive processes for the updated models.

Fig. 3 shows the scattering of muon numbers vs. electron numbers for vertical showers of different energies which might be observed by the KASCADE-Grande experiment (Bertaina et al., 2001). With increasing primary energy the relative fluctuations are reduced, but a separation between proton and iron induced showers is maintained.

To keep the CPU-times for these simulations at tolerable durations the *thin sampling* option available in CORSIKA has been used. This option does not treat in detail all secondary particles, rather below a selected energy threshold (here $E_{thin} = 10^{-5} \cdot E_0$) it samples 'representative' particles which are followed further on and weighted accordingly, while the remaining huge bulk of particles is skipped.

4 Highest energies

Presently three of the hadronic interaction models enable simulations of hadronic collisions with laboratory energies exceeding 10^{20} eV. Thus CORSIKA simulations of EAS induced by the most energetic primaries are possible (Risse et al., 2001) to predict in detail measurable shower parameters.

An interesting quantity is the atmospheric depth X_{max} of the shower maximum, which can be determined experimentally using fluorescence or Cherenkov techniques. It may be used to deduce the primary mass composition. Fig. 4 shows the predicted X_{max}-values of proton and iron induced showers with vertical incidence for primary energies between 10^{14} and 10^{20} eV together with experimental values.

Compared with the older SIBYLL 1.6 the X_{max}-values of version 2.1 are reduced by $\approx$ 20 g/cm^2 for proton showers and for iron showers with primary energies $\geq 10^{17}$ eV. Similarly, the evolution of QGSJET to version 01 accelerated the shower aging leading to X_{max}-values reduced by $\approx$ 12 g/cm^2 in the same range. It is remarkable that DPMJET II.5 reveals much larger X_{max}-values than the preceding version II.4, which unfortunately did not reach up to the highest energies. But the X_{max}-values of this older version agreed much better with those of NEXUS 2 and SIBYLL 2.1.

5 Outlook

A considerable progress in describing the inelastic hadron-air cross-sections up to 10^{15} eV can be stated during the last years. E.g. the variations in the inelastic p-air cross-sections adopted for the different interaction models have shrunk from 18 % in 1997 to today's 6 % around the average of 390 mb at 10^{15} eV. Similarly, the quality of predicted shower quantities has been improved. The differences of the average electron size at sea level for 10^{15} eV vertical proton induced EAS are reduced by a factor 3 from former 45 % to 15 % today (Knapp et al., 1996; Knapp, 1999) if we compare the results generated by the four modern models with those generated by the models available in 1996.

A further improvement of the hadronic interaction models may be expected in near future: DPMJET version 3 is announced (Roesler et al., 2000), works on NEXUS 3 succeeding version 2 are going on, and a more advanced version

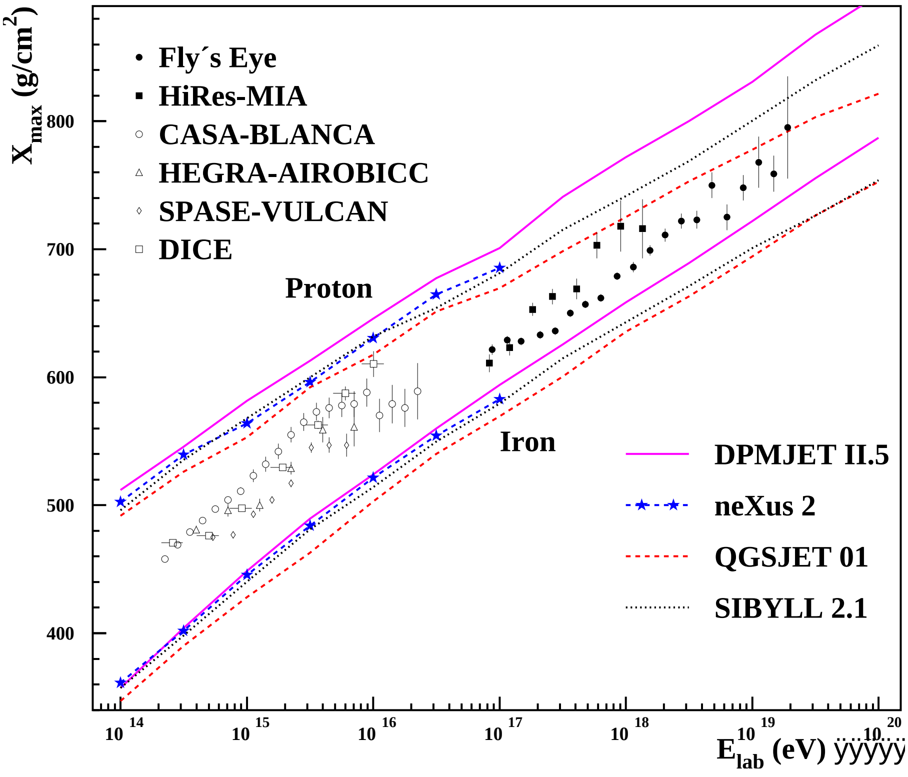

Fig. 4. Depth of shower maximum X_{max} of charged particles as function of primary energy for vertical showers as predicted by CORSIKA coupled with various models. The procedure to derive the X_{max}-values is similar to that described by (Pryke, 2001). A modified Gaisser-Hillas function (Gaisser and Hillas, 1977) has been fitted to the longitudinal distribution of each of the 500 proton or 200 iron induced showers at each of the 13 individual energies. Averaging the fitted X_{max}-parameters for each energy and primary particle gives the resulting X_{max}-values. Measurement points of fluorescence experiments (Bird el al., 1993; Abu-Zayyad et al., 2000) are indicated by filled symbols, those of Cherenkov experiments (Fowler et al., 2001; Arqueros et al., 2000; Dickinson et al., 1999; Swordy and Kieda, 2000) by open symbols.

of SIBYLL might become available soon (Engel, 2001).

6 Program distribution

The CORSIKA 6.00 program files including an up-to-date version of the User's Guide (Knapp and Heck, 1993) are available via anonymous ftp from **ftp-ik3.fzk.de**. Details for access to this anonymous account may be found on the web page **http://www-ik3.fzk.de/˜heck/corsika/** .

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