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The event generator DPMJET-III at cosmic ray energies

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Abstract. A new version of the Monte Carlo event generator DPMJET for air shower simulations is presented. It is a code system based on the Dual Parton Model and combines all features of the DTUNUC-2, DPMJET-II and PHOJET 1.12 event generators. DPMJET-III allows the simulation of hadron-hadron, hadron-nucleus, nucleus-nucleus, photon-hadron, photon-photon and photon-nucleus interactions from a few GeV up to the highest cosmic ray energies.

1 Introduction

Hadronic collisions at high energies involve the production of particles with low transverse momenta, the so-called *soft* multiparticle production. The theoretical tools available at present are not sufficient to understand this feature from QCD and phenomenological models are typically applied instead. The Dual Parton Model (DPM) (Capella et al., 1994) is such a model and its fundamental ideas are presently the basis of many of the Monte Carlo (MC) implementations of soft interactions in codes used for cosmic ray shower simulations.

Many of these implementations are however limited in their application, for example with respect to the energy range or the collision partners (hadrons, nuclei, photons) which the model can be used for.

In this paper we present the DPMJET-III code system, a MC event generator based on the DPM which is unique in its wide range of application. DPMJET-III is capable of simulating hadron-hadron, hadron-nucleus, nucleus-nucleus, photon-hadron, photon-photon and photon-nucleus interactions from a few GeV up to the highest cosmic ray energies.

2 The Concept of the Program

DPMJET-III is the result of merging all features of the event generators DPMJET-II (Ranft, 1995) and DTUNUC-2 (Roesler et al., 1998) into one single code system. The latter two codes are similar in their underlying concepts, however they differ in the Monte Carlo realization of these concepts, in particular, of the DPM.

Whereas individual nucleon-nucleon collisions in DPMJET-II are simulated based on the DTUJET model (Aurenche et al., 1992), DTUNUC-2 is using PHOJET1.12 (Engel, 1995; Engel and Ranft, 1996). Using PHOJET for calculating hadron-hadron interactions and hadronic interactions involving photons, DTUNUC-2 allows also the simulation of photoproduction off nuclei.

However, many program modules in DPMJET-II and DTUNUC-2 are also identical. Examples are the Glauber-Gribov formalism for the calculation of nuclear cross sections (Shmakov et al., 1989), the formation-zone intranuclear cascade (Ranft, 1988), the treatment of excited nuclei (Ferrari et al., 1996a,b) and the HADRIN-model for the description of interactions below 5 GeV (Hänßgen and Ranft, 1986).

The core of DPMJET-III consists of DTUNUC-2 and PHOJET1.12. In addition all those features of DPMJET-II were added which were not part of DTUNUC-2 so far. This includes, for example, quasi-elastic neutrino interactions (Battistoni et al., 1998) and baryon-stopping diagrams (Ranft et al., 2000, 2001).

3 Models Implemented in DPMJET-III

3.1 The Realization of the Dual Parton Model

The DPM combines predictions of the large N_c, N_f expansion of QCD (Veneziano , 1974) and assumptions of duality (Chew and Rosenzweig, 1978) with Gribov's reggeon field theory (Gribov, 1968). PHOJET, being used for the simulation of elementary hadron-hadron, photon-hadron and photon-photon interactions with energies greater than 5 GeV, implements the DPM as a two-component model using reggeon theory for soft and perturbative QCD for hard interactions. In addition to the model features as described in detail in Engel (1997), the version 1.12 incorporates a model for

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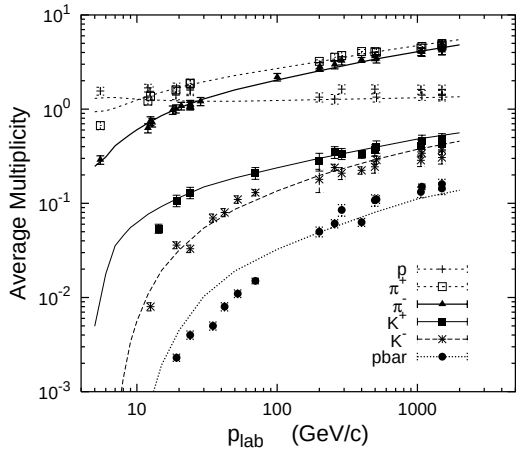

Fig. 1. Average particle multiplicity proton-proton interactions. DPMJET-III results (curves) are compared to experimental data (symbols).

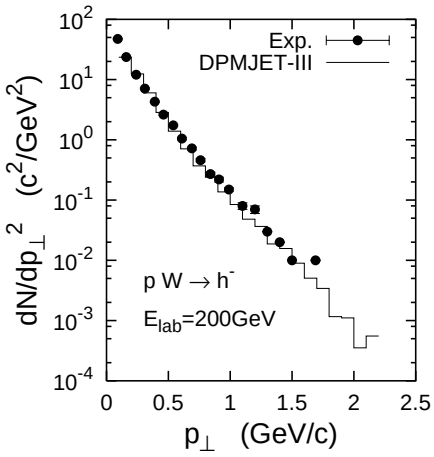

Fig. 2. Transverse momentum distribution of negative hadrons in proton-tungsten interactions 200 GeV.

high-mass diffraction dissociation including multiple jet production and recursive insertions of enhanced pomeron graphs (triple-, loop- and double-pomeron graphs). In the following only the new features are briefly discussed.

High-mass diffraction dissociation is simulated as pomeron-hadron or pomeron-pomeron scattering, including multiple soft and hard interactions (Bopp et al., 1998). To account for the nature of the pomeron being a quasi-particle, the CKMT pomeron structure function (Capella et al., 1996) with a hard gluonic component is used. These considerations refer to pomeron exchange reactions with small pomeron-momentum transfer, $|t^2|$. For large $|t^2|$ the rapidity gap production (e.g. jet-gap-jet events) is implemented on the basis the color evaporation model (Eboli et al., 1998).

Extrapolating the two-channel eikonal-unitarization of a hadron-hadron amplitude as used in PHOJET to large cosmic ray energies raises the question of the treatment of enhanced graphs which become more and more important at high energy and lead to large multiplicity fluctuations. A full amplitude calculation including enhanced graphs is very involved and not suited for a Monte Carlo implementation. Therefore, based on the results of Kaidalov et al. (1986), a simpler approach is used of interpreting each soft pomeron as the sum of a series of a bare soft pomeron and enhanced graphs (Froissaron). In practice, this results in the simulation of possibly recursive subdivisions of a single Froissaron cut into various other configurations such as, for example, two cut pomerons or a single cut pomeron and a diffractive scattering. However, the current implementation should only be considered as a first step toward a consistent treatment of enhanced graphs at very high energy because of its limitation to soft interactions.

3.2 Hadronic Interactions Involving Photons

The photon is assumed to be a superposition of a *bare* photon interacting in direct processes and a *hadronic* photon interacting in resolved processes.

The description of interactions of the hadronic photon with nuclei is based on the Generalized Vector Dominance Model (GVDM) (Donnachie and Shaw, 1978). Photons are assumed to fluctuate into quark-antiquark states of a certain mass M and the interaction is described as scattering of the hadronic fluctuation on the nucleus. The model is limited to low photon-virtualities Q^2 satisfying the relation $Q^2 \ll 2m_N\nu$ (ν and m_N being the photon energy and nucleon mass). For individual $q\bar{q}$-nucleon interactions it is sufficient to consider only two generic $q\bar{q}$-states, the first one grouping ρ^0, ω and ϕ and $\pi^+\pi^-$-states up to the ϕ-mass together and the second one including all $q\bar{q}$-states with higher masses (Engel, 1995).

Direct photon interactions are treated as either quark-gluon Compton scattering or photon-gluon fusion processes on a single nucleon. The consideration of so-called anomalous interactions allows a steady transition between direct and resolved interactions (Roesler et al., 1998).

3.3 The Gribov-Glauber Multiple Scattering Formalism

The Monte Carlo realization of the Gribov-Glauber multiple scattering formalism follows the algorithms of Shmakov et al. (1989) and allows the calculation of total, elastic, quasi-elastic and production cross sections for any high-energy nuclear collision. Parameters entering the hadron-nucleon scattering amplitude (total cross section and slope) are calculated within PHOJET.

For photon-projectiles ideas of the GVDM have been incorporated in order to correctly treat the mass of the hadronic fluctuation and its coherence length as well as pointlike photon interactions. Realistic nuclear densities and radii are used for light nuclei and Woods-Saxon densities otherwise.

During the simulation of an inelastic collision the above formalism samples the number of "wounded" nucleons, the impact parameter of the collision and the interaction configurations of the wounded nucleons. Individual hadron (photon, nucleon)-nucleon interactions are then described by PHOJET

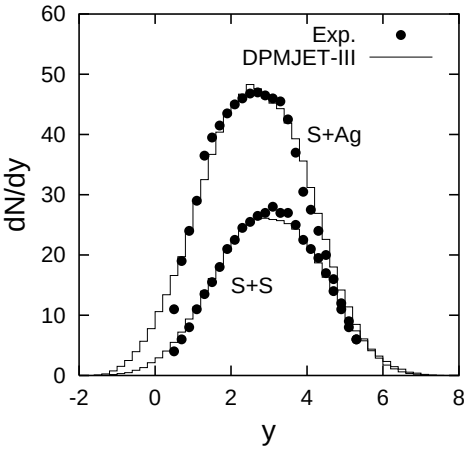

Fig. 3. Rapidity distributions of negative hadrons in central nuclear collisions at 200 GeV/nucleon.

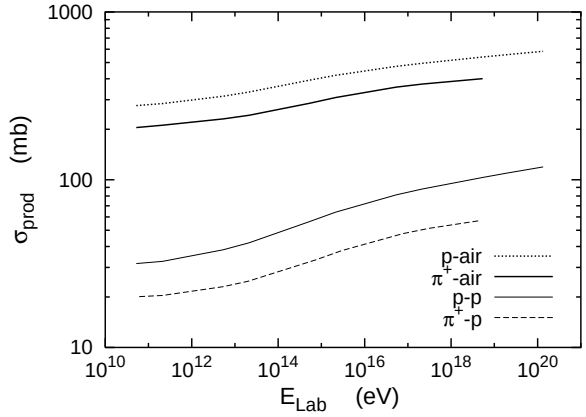

Fig. 4. Inelastic particle production cross section for proton-proton, pion-proton, proton-air and pion-air interactions.

including multiple hard and soft pomeron exchanges, initial and final state radiation as well as diffraction.

As a new feature, DPMJET-III allows the simulation of enhanced graph cuts in non-diffractive inelastic hadron-nucleus and nucleus-nucleus interactions. For example, in an event with two wounded nucleons, the first nucleon might take part in a non-diffractive interaction whereas the second one scatters diffractively producing only very few secondaries. Such graphs are predicted by the Gribov-Glauber theory of nuclear scattering but are usually neglected.

3.4 Intranuclear Cascade and Break-up of Excited Nuclei

The treatment of intranuclear cascades in spectator prefragments and their subsequent fragmentation is largely identical to the one described by Ferrari et al. (1996a,b). Particles created in string fragmentation processes are followed on straight trajectories in space and time. A certain formation time is required before newly created particles can re-interact in the spectator nuclei. These re-interactions are of low energy and are described by HADRIN (Hänßgen and Ranft, 1986) based on parameterized exclusive interaction channels. In nucleus-nucleus collisions the intranuclear cascade is calculated for both the projectile and target spectators.

Excitation energies of prefragments are calculated by summing up the recoil momenta transfered to the respective prefragment by the hadrons leaving the nuclear potential (a constant average potential is assumed). The prefragments are assumed to be in an equilibrium state and excitation energy is dissipated by the evaporation of nucleons and light nuclei and by the emission of photons.

4 Comparison to Experimental Data

Since DPMJET-III is the result of merging DPMJET-II and DTUNUC-2 its predictions have to be in agreement to experimental data where there was agreement for the two latter codes before. However, this has to be proven again. Here, only a few examples are given which should represent the large amount of comparisons of DPMJET-III results with experimental data which exist.

The average multiplicity of various charged particles predicted by DPMJET-III is compared to measurements ((Geich-Gimbel, 1989) and references therein) in Fig. 1. The data are shown as function of the laboratory momentum and are reproduced well by the model. Fig. 2 shows the transverse momentum distribution of negative hadrons from p-W collisions together with data (Åkesson et al., 1990). The rapidity distributions of negative hadrons in central S-S and S-Ag collisions are compared to data (Alber et al., 1998) in Fig. 3.

5 Extrapolation to Cosmic Ray Energies

Predictions of QCD-inspired models for the highest cosmic ray energies are governed by two basic features: (i) the number of minijets produced per inelastic collision and (ii) the energy-dependence of the leading particle distribution (Engel, 1999). All models considered in the following exhibit approximately an energy-independent leading particle distribution in non-diffractive inelastic events. However, the differences in the extrapolation of the minijet cross section are substantial. For example, QGSJET (Kalmykov et al., 1997) predicts a power-law like increase of the minijet multiplicity with energy ($n_{\rm jet} \sim s^{\Delta}$, $\Delta = 0.3 \ldots 0.4$) which finally leads to very large particle multiplicities at high energy (see below). Using pre-HERA parton densities, SIBYLL 1.7 (Fletcher et al., 1994) results are driven by a rather moderate increase of the minijet cross section ($\sim \ln s$). In DPMJET the minijet cross section is calculated with an energy-dependent transverse momentum cutoff. This leads to a model which is similar to QGSJET at energies below the knee, $3 \cdot 10^{15}$ eV. Conversely, at extremly high energy, where the minijet rate is substantially reduced due to the energy-dependence of the transverse momentum cutoff, it resembles some features of SIBYLL 1.7.

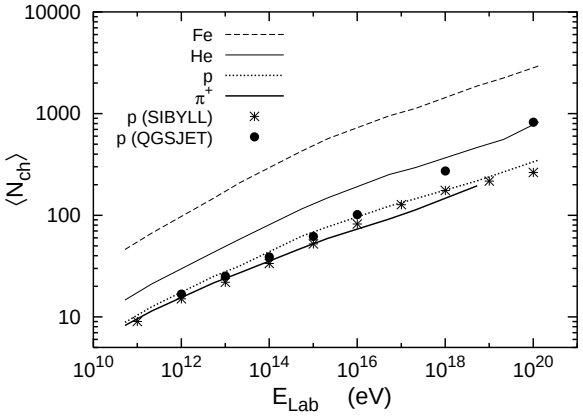

Fig. 5. Average charged particle multiplicity for proton-, pion-, helium-, and iron-air interactions as function of the laboratory energy $E_{\rm Lab}$ (in case of projectile nuclei in units of GeV/nucleon). In addition, the predictions of SIBYLL 1.7 and QGSJET are shown.

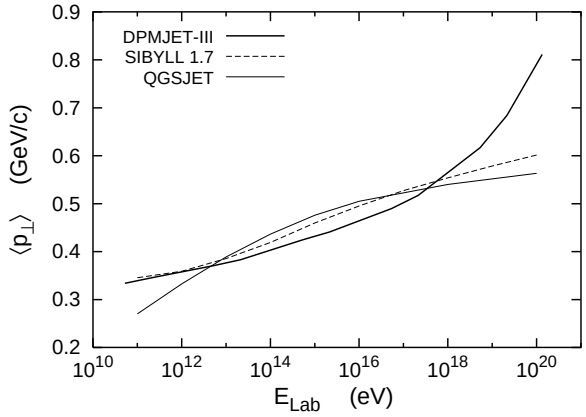

Fig. 6. Average transverse momentum of charged particles in proton-air interactions. DPMJET-III results are compared to predictions of SIBYLL 1.7 and QGSJET.

The inclusive cross section for minijet production has a steep energy dependence. However, the unitarization of elementary parton-parton interactions results in a weak energy dependence of the total cross section for particle production, as shown in Fig. 4.

Predictions on average multiplicities of charged particles produced in inelastic collisions are given in Fig. 5. Results calculated with SIBYLL 1.7 and QGSJET for proton-air interactions are also shown. As expected, the multiplicities predicted by DPMJET-III and SIBYLL 1.7 are rather similar at very high energy.

Finally, in Fig. 6 average transverse momenta predicted by DPMJET-III, SIBYLL 1.7, and QGSJET are shown. This plot clearly demonstrates that, although the total minijet cross sections are rather similar in DPMJET-III and SIBYLL 1.7, the physics assumptions of both models are different. The rapid increase of the average transverse momentum in DPMJET-III is a characteristic feature of models implementing partonic shadowing or saturation for low-$p_\perp$ minijets (Engel, 1999).

6 Conclusions

A new version of the DPMJET event generator is presented and applied to cosmic ray energies. DPMJET-III is based on DPMJET-II, DTUNUC-2 and PHOJET1.12 and unifies all features of these three event generators in one single code system. The code is available on request from the authors.

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