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 629–632

Hadronic Interaction Model EPOS and Air Shower Simulations: New Results on Muon Production.

T. PIEROG[1] AND K. WERNER[2].
[1] *Forschungszentrum Karlsruhe, Institut für Kernphysik, Karlsruhe, Germany*
[2] *SUBATECH, University of Nantes – IN2P3/CNRS– EMN, Nantes, France*
pierog@ik.fzk.de

Abstract: Since about one decade, air shower simulations based on the hadronic interaction models QGSJET and SIBYLL predict very similar results for the main observables. For instance, the mean depth of the shower maximum Xmax agrees within 5% between the different models and are in relative good agreement with the measurements. However the number of muons at ground differs substantially between these 2 models and the data. Recently a new hadronic interaction model EPOS has been introduced in air shower simulation programs. This model has originally been used to analyse hadron-hadron as well as heavy ion physics at RHIC and SPS energies, and it gives very interesting results in air shower simulations: we find for example a large increase in the number of muons at ground as compared to the former models. Results will be discussed in detail, in particular the role of the baryons and anti-baryons in the air shower development.

Introduction

Air shower simulations are a very powerful tool to interpret ground based cosmic ray experiments. However, most simulations are still based on hadronic interaction models being more than 10 years old. Much has been learned since, in particular due to new data available from the SPS and RHIC accelerators.

In this paper, we discuss air shower simulations based on EPOS, the latter one being a hadronic interaction model, which does very well compared to RHIC data [1, 2], and also all other available data from high energy particle physic experiments (ISR, CDF and especially SPS experiments at CERN).

EPOS is a consistent quantum mechanical multiple scattering approach based on partons and strings [3], where cross sections and the particle production are calculated consistently, taking into account energy conservation in both cases (unlike other models where energy conservation is not considered for cross section calculations [4]). A special feature is the explicit treatment of projectile and target remnants, leading to a very good description of baryon and antibaryon production as measured in proton-proton collisions at 158 GeV at CERN [5]. Nuclear effects related to Cronin transverse momentum broadening, parton saturation, and screening have been introduced into EPOS [6]. Furthermore, high density effects leading to collective behavior in heavy ion collisions are also taken into account [7].

EPOS Basics

One may consider the simple parton model to be the basis of high energy hadron-hadron interaction models, which can be seen as an exchange of a "parton ladder" between the two hadrons. In EPOS, the term "parton ladder" is actually meant to contain two parts [3]: the hard one, as discussed above, and a soft one, which is a purely phenomenological object, parameterized in Regge pole fashion.

In additions to the parton ladder, there is another source of particle production: the two off-shell remnants, see fig. 1. We showed in ref. [5] that this "three object picture" can solve the "multistrange baryon problem" of conventional high energy models, see ref. [8].

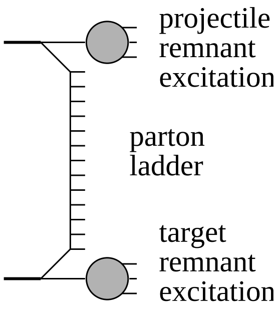

Figure 1: Elementary parton-parton scattering: the hard scattering in the middle is preceded by parton emissions attached to remnants. The remnants are an important source of particle production even at RHIC energies.

Multiple scattering is introduced based on Gribov's multiple scattering theory, as in other models, in order to ensure unitarity. In EPOS, however, we explicitly care about the fact that the total energy has to be shared among the individual elementary interactions. This is usually ignored, although it is required by theoretical consistency.

A consistent quantum mechanical formulation of the multiple scattering requires not only the consideration of the (open) parton ladders, discussed so far, but also of closed ladders, representing elastic scattering.The closed ladders do not contribute to particle production, but they are crucial since they affect substantially the calculations of partial cross sections. Actually, the closed ladders simply lead to large numbers of interfering contributions for the same final state, all of which have to be summed up to obtain the corresponding partial cross sections. It is a unique feature of our approach to consider explicitly energy-momentum sharing at this level (the "E" in the name EPOS).

Energy momentum sharing and remnant treatment are the key points of the model concerning air shower simulations because they directly influence the multiplicity and the inelasticity of the model. Some other new features – not discussed here but important for particle physic and accelerator data comparisons – are the treatment of high density effects, described in [6, 7].

Air Shower Simulations

In the following, we discuss air shower simulations, based on the shower programs CORSIKA[9] or CONEX[10], using EPOS or QGSJET II-3[11] (as a reference) as interaction model.

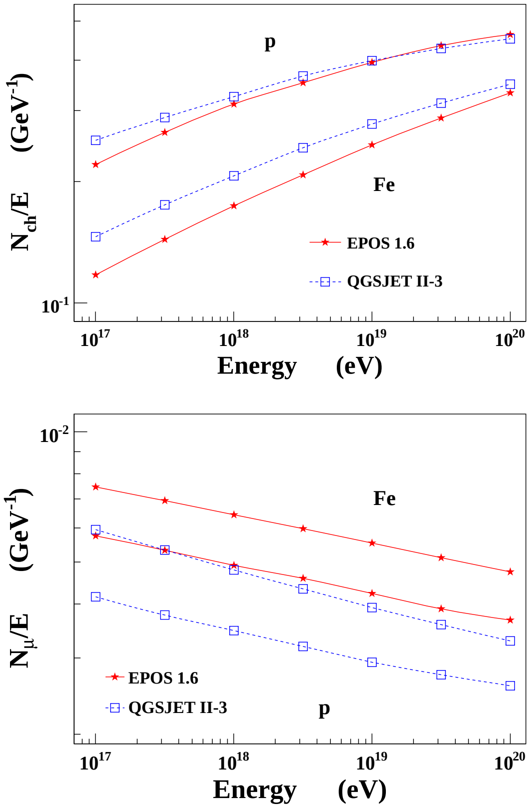

Figure 2: Total number of charged particles (upper plot) and muons (lower plot) at ground divided by the primary energy as a function of the primary energy for proton and iron induced shower using EPOS (full lines) and QGSJET II-3 (dotted lines) as high energy hadronic interaction model.

Air shower simulations are very important to analyze the two most common type of high energy cosmic ray experiments: fluorescence telescopes and surface detectors. In the first ones, one observes directly the longitudinal shower development, from which the energy and the depth of shower maximum $X_{\max}$ can be extracted. Comparing the latter with models allows us to have informations on the mass of the primary. EPOS results concerning $X_{\max}$ are in good agreement with former models and experimental data as shown in [12].

Concerning particles measured at ground by air shower experiment, the situation is quite different. Whereas the number of charged particles is very similar for EPOS and QGSJET II-3 (see fig. 2), EPOS produces a much higher muon flux, in particular at high energy. At 10^{20} eV EPOS is more than 40% higher and gives even more muons with a primary proton than QGSJET II-3 for iron induced showers.

The muon excess from EPOS compared to other models will affect all experimental observables depending on simulated muon results. In the case of the Pierre Auger obervatory (PAO), this will affect mostly the results on inclined showers, for which the electromagnetic component is negligible at ground. It is interesting to notice that the PAO claims a possible lack of muons in air showers simulated with current hadronic interaction models [13].

The muon production process

During the hadronic air shower development, the energy is shared between neutral pions which convert their energy into the electromagnetic component of the shower, and charged hadrons which continue the hadronic cascade producing muons [14]. The ratio of the two (referred to as R) is a measure of the muon production.

Comparing EPOS to other models, this ratio R of neutral pions to charged hadrons produced in individual hadronic interactions is significantly lower, especially for pi-air reactions, as seen in fig. 3. This will increase the muon production, as discussed above.

Furthermore, the reduced ratio R is partly due to an enhanced baryon production, as shown in fig. 4. This will increase the number of baryon initiated sub-showers. Since the ratio R is much softer in case of proton-air interactions compared to pion-air interactions, as shown in fig. 5, this will even more reduce R, providing a significant additional source of muons. Indeed, simulations show that a pion induced shower produces about 30% less

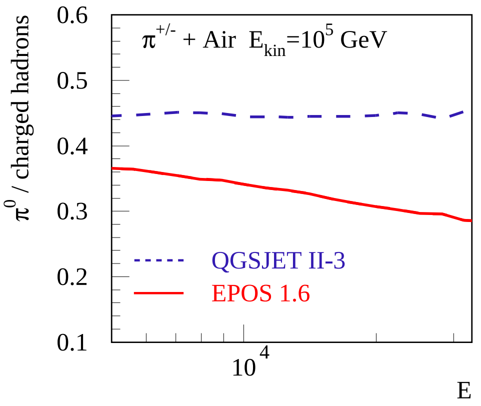

Figure 3: Ratio of the number of π^0 over the number of charged particles as a function of the energy of the secondary particles at 10^5 GeV kinetic energy with EPOS (full line) or QGSJET II-3 (dashed line) in pion-air.

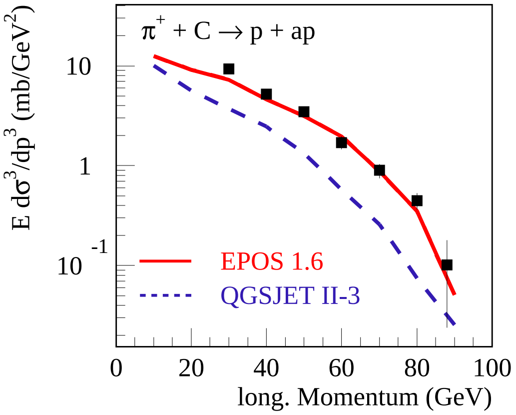

Figure 4: Model comparison: longitudinal momentum distributions of protons in pion carbon collisions at 100 GeV from EPOS (full) and QGSJET II-3 (dashed) compared to data[15].

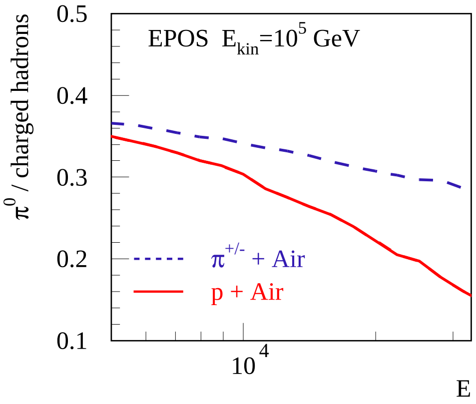

Figure 5: Ratio of the number of π^0 over the number of charged particles as a function of the energy of the secondary particles at 10^5 GeV kinetic energy in proton-air (full line) or pion-air (dashed line) for EPOS.

muons than a proton induced shower. This feature of the air shower development is in fact model independent and can easily be understood because of the leading particle effect [16].

Summary

EPOS is a new interaction model constructed on a solid theoretical basis. It has been tested very carefully against all existing hadron-hadron and hadron nucleus data, also those usually not considered important for cosmic rays. In air shower simulations, EPOS provides more muons than other models, which was found to be linked to an increased baryon production.

Acknowledgments

The authors would like to thanks Ralph Engel, Dieter Heck and Sergej Ostapchenko for fruitful discussions.

References

[1] R. Bellwied, Strange particle production mechanisms in proton proton collisions at rhic, Acta Phys. Hung. A27 (2006) 201–204.
[2] B. I. Abelev, et al., Strange particle production in p + p collisions at s**(1/2) = 200-gev, nucl-ex/0607033 (2006).
[3] H. J. Drescher, et al., Parton-based gribov-regge theory, Phys. Rept. 350 (2001) 93–289.
[4] M. Hladik, et al., Self-consistency requirement in high-energy nuclear scattering, Phys. Rev. Lett. 86 (2001) 3506–3509.
[5] F. M. Liu, et al., Constraints on models for proton-proton scattering from multistrange baryon data, Phys. Rev. D67 (2003) 034011.
[6] K. Werner, et al., Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron gold collisions at rhic, Phys. Rev. C74 (2006) 044902.
[7] K. Werner, Core-corona separation in ultra-relativistic heavy ion collisions, Phys. Rev. Lett. 98 (2007) 152301.
[8] M. Bleicher, et al., Overpopulation of anti-omega in p p collisions: A way to distinguish statistical hadronization from string dynamics, Phys. Rev. Lett. 88 (2002) 202501.
[9] D. Heck, et al., Corsika: A monte carlo code to simulate extensive air showers, fZKA-6019 (1998).
[10] T. Bergmann, et al., One-dimensional hybrid approach to extensive air shower simulation, Astropart. Phys. 26 (2007) 420–432.
[11] S. Ostapchenko, Non-linear screening effects in high energy hadronic interactions, Phys. Rev. D74 (2006) 014026.
[12] T. Pierog, et al., Latest results of air shower simulation programs corsika and conex, These proceedings #0899.
[13] R. Engel, et al., Test of hadronic interaction models with data from the pierre auger observatory, These proceedings #0605.
[14] T. Pierog, et al., Impact of uncertainties in hadron production on air-shower predictions, Czech. J. Phys. 56 (2006) A161–A172.
[15] D. S. Barton, et al., Experimental study of the a-dependence of inclusive hadron fragmentation, Phys. Rev. D27 (1983) 2580.
[16] T. Pierog, K. Werner, astro-ph/0611311.