Extended Air Shower Simulations Based on EPOS

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Abstract

We discuss air shower simulations based on the EPOS hadronic interaction model. A remarkable feature is the fact that the number of produced muons is considerably larger compared to other interaction models. We show that this is due to an improved treatment of baryon-antibaryon production.

1 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 15 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].

2 EPOS Basics

One may consider the simple parton model to be the basis of hadron-hadron interaction models at high energies. It is well known that the inclusive cross section is given as a convolution of two parton distribution functions with an elementary parton-parton interaction cross section. The latter one is obtained from perturbative QCD, the parton distributions are deduced from deep inelastic scattering. Although these distributions are taken as black boxes, one should not forget that they represent a dynamical process, namely the successive emission of partons (initial state space-like cascade), as shown in fig. 1(a). We refer to this whole structure as "parton ladder", with a corresponding simple symbol as shown in fig. 1(b), to simplify further discussion.

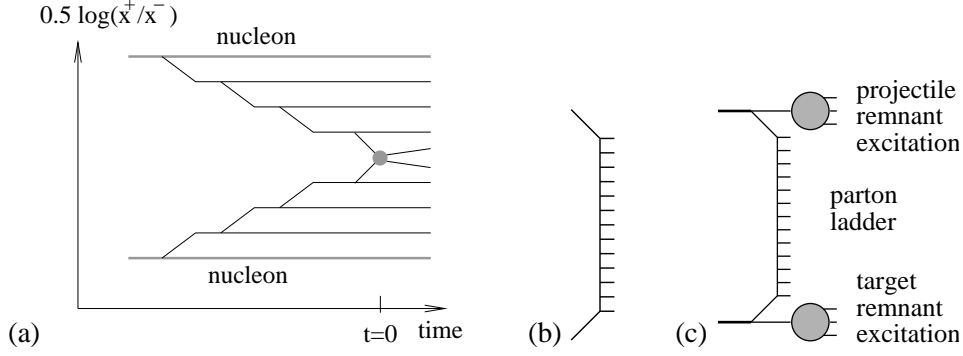
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Fig. 1: (a) Elementary parton-parton scattering: the hard scattering in the middle is preceded by parton emissions (initial state space-like cascade). (b) Symbolic parton ladder, representing the structure shown left. (c) The complete picture, including remnants. The remnants are an important source of particle production at RHIC energies.

Actually our "parton ladder" is meant to contain two parts [3]: the hard one, as discussed above, and a soft one, which is a purely phenomenological object, parametrized in Regge pole fashion.

Still the picture is not complete, since so far we just considered two interacting partons, one from the projectile and one from the target. These partons leave behind a projectile and target remnant, colored, so it is more complicated than simply projectile/target deceleration. One may simply consider the remnants to be diquarks, providing a string end, but this simple picture seems to be excluded from strange antibaryon results at the SPS [8].

We therefore adopt the following picture, as indicated in fig. 1(c): not only a quark, but a two-fold object takes directly part in the interaction, being a quark-antiquark, or a quark-diquark, leaving behind a colorless remnant, which is, however, in general excited (off-shell). So we have finally three "objects", all being white: the two off-shell remnants, and the parton ladders between the two active "partons" on either side (by "parton" we mean quark, antiquark, diquark, or antidiquark). We showed in ref. [5] that the "three object picture" as discussed in this paper can solve the "multi-strange baryon problem" of ref. [8].

Even inclusive measurements require often more information than just inclusive cross sections, for example via trigger conditions. Anyhow, for detailed comparisons we need an event generator, which obviously requires information about exclusive cross sections (the widely used pQCD generators are not event generators in this sense, they are generators of inclusive spectra, and a Monte Carlo event is not a physical event). This problem is known since many years, the solution is Gribov's multiple scattering theory, employed since by many authors. This formulation is equivalent to using the eikonal formula to obtain exclusive cross sections from the knowledge of the inclusive one.

We indicated recently inconsistencies in this approach, proposing an "energy conserving multiple scattering treatment" [3]. The main idea is simple: in case of multiple scattering, when it comes to calculating partial cross sections for double, triple ... scattering, one has to explicitly care about the fact that the total energy has to be shared among the individual elementary
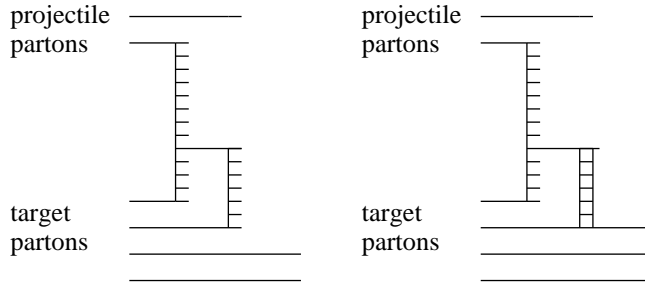
Fig. 2: Inelastic and elastic "rescattering" of a parton from the parton ladder with a second target parton. We talk about (inelastic and elastic) splitting of a parton ladder.

interactions.

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).

3   Splitting of Parton Ladders

Let us consider very asymmetric nucleus-nucleus collisions, like proton-nucleus or deuteron-nucleus. The formalism developed earlier for pp can be generalized to these nuclear collisions, as long as one assumes that a projectile parton always interacts with exactly one parton on the other side, elastically or inelastically (realized via closed or open parton ladders). We employ the same techniques as already developed in the previous section. The calculations are complicated and require sophisticated numerical techniques, but they can be done.

In case of protons (or deuterons) colliding with heavy nuclei (like gold), there is a complication, which has to be taken into account: suppose an inelastic interaction involving an open parton ladder, between a projectile and some target parton. The fact that these two partons interact implies that they are close in impact parameter (transverse coordinate). Since we have a heavy target, there are many target partons available, and among those there is a big chance to find one which is as well close in impact parameter to the two interacting partons. In this case it may be quite probable that a parton from the ladder interacts with this second target parton, inelastically or elastically, as shown in fig. 2.

The main effect of elastic splittingis suppression of small light cone momenta, which agrees qualitatively with the concept of saturation. But this is only a part of the whole story, several other aspects have to be considered [6]. Consider the example shown in figure 2(left). In the upper part, there is only an ordinary parton ladder, so we expect "normal" hadroniza-

tion. In the lower part, we have two ladders in parallel, which are in addition close in space, since they have a common upper end, and the lower ends are partons close in impact parameter, so the hadronization of the two ladders is certainly not independent, we expect some kind of a "collective" hadronization of two interacting ladders. Here, we only considered the most simple situation, one may also imagine three or more close ladders, hadronizing collectively.

The strength of the effects due to parton ladder splitting will depend on the target mass, via the number Z of partons available for additional legs. The number Z of available partons will also increase with energy, so at high enough energy the above-mentioned effects can already happen in pp collisions.

A quantitative discussion how the above-mentionned effects are realized may be found in [6].

4 Air Shower Simulations

In the following, we discuss air shower simulations, based on the shower programs CORSIKA [9] or CONEX [10, 11], using EPOS or QGSJET II-3 [12] (as a reference) as interaction model.
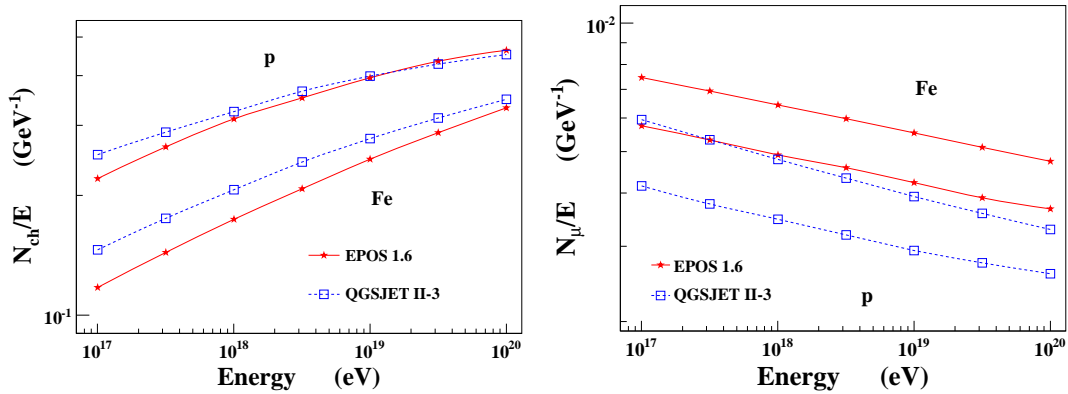

Fig. 3: Total number of charged particles (left plot) and muons (right plot) at ground divided by the primary energy as a function of the primary energy for proton and iron induced shower using EPOS (full lines) and QGSJET II-3 (dotted lines) as high energy hadronic interaction model.

Air shower simulations are very important to analyze the two most common types 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.

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. 3), EPOS produces a much higher muon flux, in particular at high energy. At
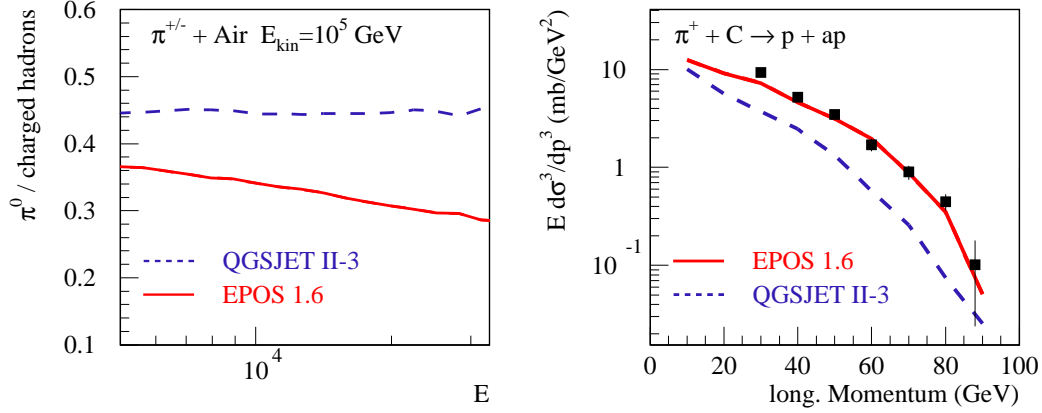
Fig. 4: Left: Ratio of the number of π^0 over the number of charged particles as a function of the energy of the secondary particles at 10^5 GeV kinetic energy with EPOS (full line) or QGSJET II-3 (dashed line) in pion-air. Right: Longitudinal momentum distributions of protons in pion carbon collisions at 100 GeV from EPOS (full) and QGSJET II-3 (dashed) compared to data.

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.

5 The origin of the increased muon production

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. 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. 4(left). 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(right) (data from [13]). 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, this will even more reduce R, providing a significant additional source of muons.

6 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.

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