How to Relate Particle Physics and Air Shower Development : the EPOS Model

Tanguy Pierog*, **Klaus Werner**†

*Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, Karlsruhe, Germany
†SUBATECH, Université de Nantes - IN2P3/CNRS - EMN, Nantes, France

***Abstract*. In 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. Recently a new hadronic interaction model EPOS 1.61 has been introduced in air shower simulation programs. This model has originally been used to analyze hadron-hadron as well as heavy ion physics at RHIC and SPS energies. Used for air showers, it gives a much larger number of muons at ground. The cross section of this model being too high, the correlation between the number of muons and the number of electrons at ground was not consistent with the KASCADE measurements. New developments in EPOS lead to a strong reduction of the proton-nucleus cross section whose consequences are important both for LHC predictions and air shower measurement. In this contribution, we will show the results of the new version of EPOS 1.99 and how cosmic ray physic can be used to constrain particle physic.**

***Keywords*: EPOS, air-shower, simulation**

I. 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], and also other particle physic experiments (especially SPS experiments at CERN). But used in air shower simulation program like CORSIKA [2] or CONEX [3], some results where in contradiction with KASCADE data [4], while it was better for other experiments [5].

Due to the constrains of particle physics, air shower simulations using EPOS present a larger number of muons at ground [6]. On the other hand, we will explain in this paper, how the constrains given by cosmic ray experiments can compensate the lack of accelerator data in some given kinematic regions (very forward) to improve hadronic interaction models and in particular the new EPOS 1.99.

II. EPOS MODEL

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.

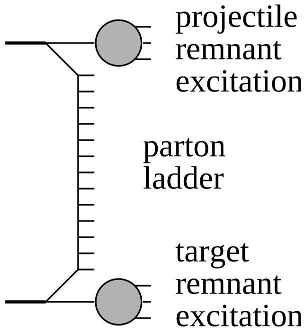

Fig. 1. Elementary parton-parton scattering: the hard scattering in the middle is preceded by parton emissions attached to remnants. The remnants are an important source of particle production even at RHIC energies.

In EPOS, the term "parton ladder" is actually meant to contain two parts [7]: 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. [8] that this "three object picture" can solve the "multi-strange baryon problem" of conventional high energy models, see ref. [9].

Hence EPOS is a consistent quantum mechanical multiple scattering approach based on partons and strings [7], 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 [10]). Nuclear effects related to Cronin transverse momentum broadening, parton saturation, and screening have been introduced into EPOS [11]. Furthermore, high density effects leading to collective behavior in heavy ion collisions are also taken into account [12].

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. At very high energies or high densities, the so-called non-linear ef-

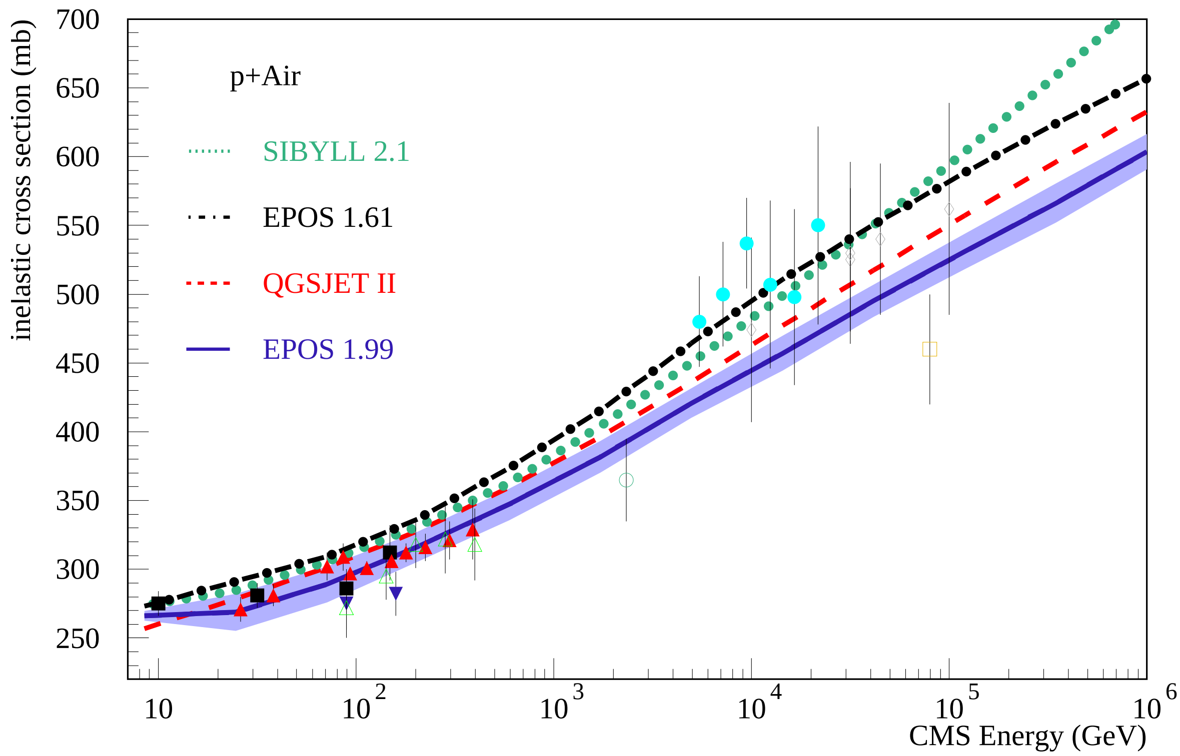

Fig. 2. Inelastic cross section of proton-air interactions. EPOS 1.99, QGSJETII, EPOS 1.61 and SIBYLL 2.1 hadronic interaction models (lines) are compared to data of air shower experiment (points).

fects described in [11] are particularly important for the extrapolation for EAS and it's one of the parts which has been changed in EPOS 1.99.

A. Cross section

We learned from KASCADE data [4], that the energy carried by hadrons in EPOS 1.61 simulations is too low. It means than the showers are too old when they reach ground and it was due to a problem in the calculation of the nuclear cross section and to a too large remnant break-up at high energy (leading to a high inelasticity).

To improve the predictive power of the model, the effective treatment of non-linear effects describe in [11] has been made consistent to describe both proton-proton, hadron-nucleus and nucleus-nucleus data with a unique saturation scale which can be fixed thanks to proton-proton cross section and Cronin effect in dAu collisions at RHIC. Details will be published in a dedicated article.

The EPOS 1.99 (full line) proton-carbon total cross section is shown Fig 3. It is now in very good agreement with the data [13] and with the other hadronic interaction models used for air shower physics QGSJET01 [14] (dashed-dotted line), QGSJETII [15] (dashed line) and SIBYLL [16] (dotted line). In fig 2, the extrapolation to proton-air data up to the highest energies is shown in comparison with measurement from cosmic ray experiments. The surface around the line for EPOS 1.99 represents the uncertainty due to the definition of the

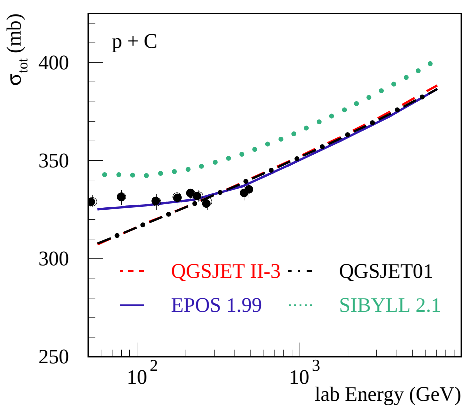

Fig. 3. Total cross section of proton-carbon interactions. EPOS 1.99, QGSJETII, QGSJET01 and SIBYLL 2.1 hadronic interaction models (lines) are compared to data [13] (points)

inelastic cross section as measured by cosmic ray experiments. The difference between the top and the bottom of the area is the part of the cross-section where secondary particles are produced without changing the projectile (target diffraction). So any cross section chosen in this band would give the same result in term of air shower development. Cross section of other models includes this target diffraction (top of the band). In comparison with

EPOS 1.61 (dashed-dotted line), the EPOS 1.99 cross section has been notably reduced.

B. *Particle production and inelasticity*

Thanks to a Monte Carlo, first the collision configuration is determined: i.e. the number of each type of Pomerons exchanged between the projectile and target is fixed and the initial energy is shared between the Pomerons and the two remnants. Then particle production is accounted from two kinds of sources, remnant decay and cut Pomeron. A Pomeron may be regarded as a two-layer (soft) parton ladder attached to projectile and target remnants through its two legs. Each leg is a color singlet, of type $q\overline{q}$, qqq or $\overline{qqq}$ from the sea, and then each cut Pomeron is regarded as two strings, cf. Fig. 4a.

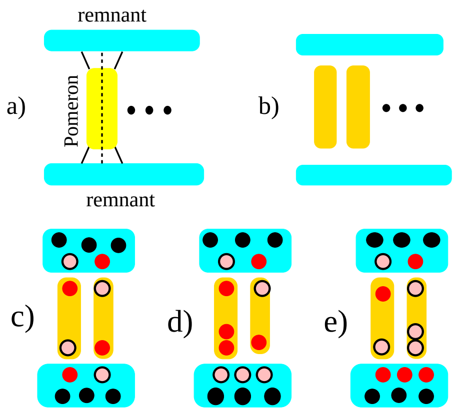

Fig. 4. a) Each cut Pomeron is regarded as two strings b). c) The most simple and frequent collision configuration has two remnants and only one cut Pomeron represented by two $q-\overline{q}$ strings. d) One of the $\overline{q}$ string ends can be replaced by a qq string end. e) With the same probability, one of the q string ends can be replaced by a $\overline{qq}$ string end.

It is a natural idea to take quarks and anti-quarks from the sea as string ends for soft Pomeron in EPOS, because an arbitrary number of Pomerons may be involved. In addition to this soft Pomerons, hard and semi-hard Pomerons are treated differently.

Thus, besides the three valence quarks, each remnant has additionally quarks and anti-quarks to compensate the flavors of the string ends, as shown in fig. 4c. According to its number of quarks and anti-quarks, to the phase space, and to an excitation probability, a remnant decays into mesons and/or (anti)baryons [8]. Furthermore, this process leads to a baryon stopping phenomenon in which the baryon number can be transfered from the remnant to the string ends (for instance in 4d, depending on the process, the $3\overline{q}+3q$ can be seen as 3 mesons or a baryon-antibaryon pair).

In case of meson projectile, this kind of diquark pair production at the string ends leads to an increase of the (anti)baryon production in the forward production

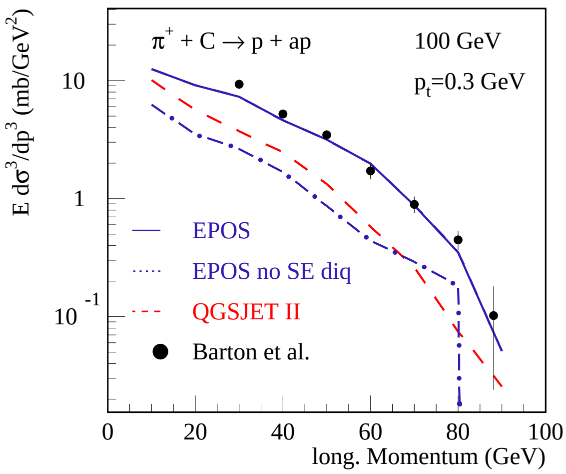

Fig. 5. Model comparison: longitudinal momentum distributions of pion carbon collisions at 100 GeV from EPOS with (full) or without (dashed-dotted) sting-end diquarks and QGSJETII (dashed) compared to data [17].

in agreement with low energy pion-nucleus data [17] as shown fig. 5. As a consequence it is part of the larger number of muons in EAS simulations with EPOS.

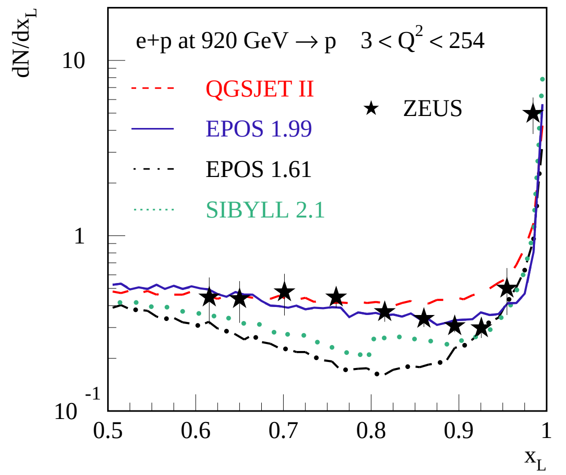

Fig. 6. Proton longitudinal momentum fraction x_{L} distribution in electron-proton interactions. EPOS 1.99 (full), QGSJETII (dashed), EPOS 1.61 (dashed-dotted) and SIBYLL 2.1 (dotted) hadronic interaction models (lines) are compared to HERA data from ZEUS experiment [18] (stars).

As shown on fig. 6, the deficit of leading proton in EPOS 1.61 was very strong around $x_{\mathrm{L}} = 0.75$. It has been corrected in EPOS 1.99. As a consequence, EPOS 1.99 has a reduced excitation probability at high energy compared to EPOS 1.61, increasing the number of protons in the forward direction and reducing the inelasticity.

III. Air showers

In the following, we discuss air shower simulations, based on the shower programs CONEX, using the old EPOS 1.61 (dashed-dotted line), the new EPOS 1.99 (full line) and QGSJETII (dashed line) (as a reference) as high energy hadronic interaction models.

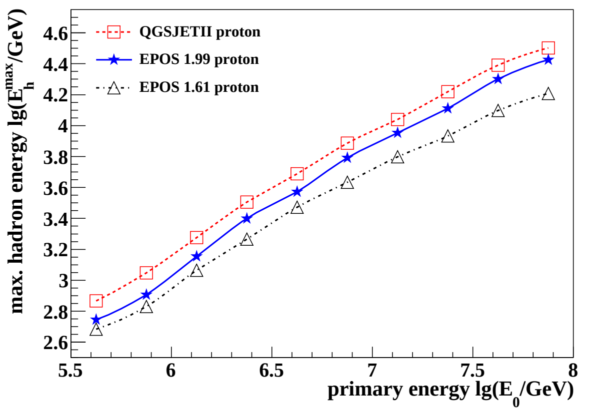

Fig. 7. Maximum hadron energy as a function of the primary energy for proton induced showers using EPOS 1.99 (full line), EPOS 1.61 (dashed-dotted line) and QGSJETII (dashed line) as high energy hadronic interaction models.

The effect of the reduced cross section and inelasticity is clearly visible on the maximum energy of hadrons at ground as shown fig. 7. The shower being younger at ground with EPOS 1.99, the maximum energy is up to 60% higher than in the previous release 1.61. The results are now close to QGSJETII results but with a different slope due to a different elongation rate.

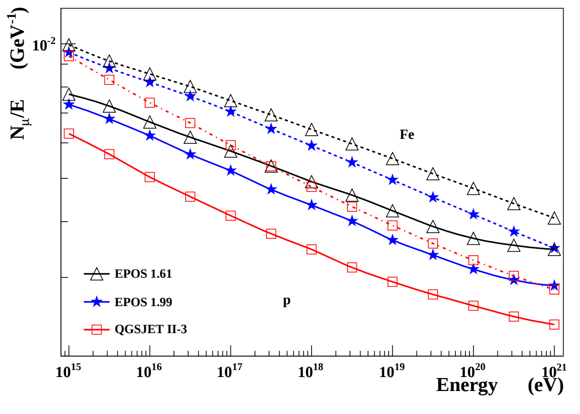

Fig. 8. Total number of muons at ground divided by the primary energy as a function of the primary energy for proton (full lines) and iron (dashed lines) induced showers using EPOS 1.99 (stars), EPOS 1.61 (triangles) and QGSJET II-3 (squares) as high energy hadronic interaction model.

Furthermore, the reduced excitation probability of the remnants leads to a reduction of the muon production compared to EPOS 1.61. Indeed, remnant break-up is an important factor of the muon production in air showers [19] in particular for the mesons. Since less excitation means less break-up, we can see on fig. 8 that EPOS 1.99 produces about 15% less muons than EPOS 1.61 (depending on the primary energy since the slope is different too). It is important to notice that air showers simulated with EPOS will still have about 25% more muons than QGSJETII at Auger energies.

As a consequence, EPOS 1.99 with less muons and more electrons and hadrons at ground does not have the problems pointed out in [4] anymore and should be compatible with KASCADE data.

IV. Summary

EPOS is an interaction model constructed on a solid theoretical basis. It has been tested very carefully against all existing hadronic data, also those usually not considered important for cosmic rays. In EAS simulations, EPOS provides more muons than other models, which was found to be linked to an increased diquark production in both string ends and string fragmentation. To solve the problems pointed out by the comparison with KASCADE data, the treatment of screening effects in nuclear collisions has been improved in EPOS. The new EPOS 1.99 has now a reduced cross section and inelasticity compared to the previous EPOS 1.61 which leads to deeper shower development. But since the number of muons and the elongation rate are different than in the other models, the resulting analysis will be significantly different.

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