Muon Production in Extended Air Shower Simulations

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Whereas air shower simulations are very valuable tools for interpreting cosmic ray data, there is a long-standing problem: it is difficult to accommodate at the same time the longitudinal development of air showers and the number of muons measured on the ground. Using a new hadronic interaction model (EPOS) in air shower simulations produces much more muons, in agreement with results from the HiRes-MIA experiment. We find that this is mainly due to a better description of (anti) baryon production in hadronic interactions. This is an aspect of air shower physics which has been neglected so far.

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For more than ten years detailed extensive air shower (EAS) simulations have played a decisive role in interpreting measurements from ground based cosmic ray measurements. This concerns, for example, the chemical composition of cosmic rays in the KASCADE experiment [1] or the primary energy determination from AGASA [2].

An air shower is initiated by a very energetic proton or nucleus (primary particle), which interacts with air by producing many secondary hadrons, which interact again, and so on. Neutral pions play a special role, since they decay into gammas which initiate an electromagnetic subshower each. The latter one is well under control (elementary processes of QED), whereas the hadronic interactions require models, being tested against accelerator data, even though they exist only at much lower energies than the highest primary energies. It turns out that more than 90% of the initial energy goes into the (well-known) electromagnetic part, whereas the rest shows up as muons from the hadronic decays. The muonic part depends therefore strongly on the hadronic modeling (up to a factor of 2 difference in different models), while the longitudinal development of the electromagnetic part (and, in particular, its maximum X_{max}) is relatively robust (less than 10% variations between models).

Using the currently employed hadronic interaction models (QGSJET 01 [3], QGSJET II [4], and SIBYLL 2.1 [5]), experiments like KASCADE [6] or HiRes-MIA [7], show inconsistencies between experimental data and simulations. Furthermore, at very high energy, the Pierre Auger Observatory finds a discrepancy between the energy reconstruction of the primary cosmic rays from two different methods: a hybrid method where the fluorescence detector is used for the surface detector calibration, and a method based partly on the muon density at ground [8] and air shower simulations. The 25% difference could be explained partly by a lack of muons in the simulations. Many attempts have been made to force the models to increase the muon production without changing the $\langle X_{max} \rangle$ (well constrained by data)—without success [9].

In this work, we discuss the consequences of introducing EPOS—a recently developed high energy hadronic interaction model—into the air shower simulation models CORSIKA [10] and CONEX [11]. A compact description of EPOS can be found in [12], many technical details about the physical basis of EPOS are described in [13], where we also discuss in detail the parameters of the model and how they are fixed. Concerning the basic features of this approach: EPOS is a consistent quantum mechanical multiple scattering approach based on partons and strings, 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 [14]). 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 [15]. Motivated by the very detailed data obtained by the RHIC experiments, nuclear effects related to Cronin transverse momentum broadening [16], parton saturation, and screening have been introduced into EPOS. Furthermore, high density effects leading to collective behavior in heavy ion collisions are also taken into account [17]. It appears that EPOS does very well compared to RHIC data [18–21], and also all other available data from high energy particle physic experiments (ISR, CDF, and especially SPS experiments at CERN [22,23]).

As a result, EPOS is the only model used both for EAS simulations and accelerator physic which is able to reproduce consistently almost all data from 100 GeV lab to 1.8 TeV center of mass energy, including antibaryons, multistrange particles, ratios and pt distributions. Since this model is applied to accelerator physics, many data are considered which are not *a priori* linked to cosmic rays and air showers. This is a very important aspect, which finally led to the discoveries discussed in this paper. The general strategy of EPOS (and its earlier versions VENUS and NEXUS) has always been to consider all possible

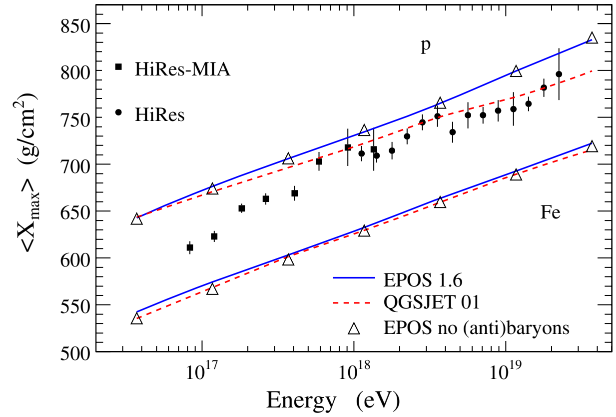

FIG. 1 (color online). The mean shower maximum $\langle X_{max} \rangle$ as measured by the HiRes-MIA [7] and the HiRes collaboration [25] as a function of primary energy, compared to proton and iron induced showers simulated with EPOS 1.6 (full lines) and QGSJET 01 (dashed lines) as high energy hadronic interaction model. The open symbols refer to EPOS without (anti) baryon production.

experimental results, and fixing parameters by going from elementary systems, like e^+e^-, towards the complex ones, like PbPb. So one first fixes pQCD cutoffs and string fragmentation parameters by studying e^+e^-, then Pomerons parameters and remnant properties by studying hadron-hadron cross sections and particle spectra, and so on. This is a complex procedure, a large fraction of [13] is devoted to this question.

For our analysis, CONEX is used to simulate the air shower development, using GHEISHA [24] as low energy hadronic interaction model below 80 GeV. For the high energy interactions (above 80 GeV) EPOS 1.6 is used, and as a reference the most commonly used interaction model QGSJET 01.

One of the most important observables in air shower physics is the electron number as a function of the depth X, the latter one representing the amount of air traversed by the shower, expressed in g/cm^2. The maximum X_{max} of this distribution is a function of the energy and of the mass of the primary particle, as shown in Fig. 1, where the results represent averages over many showers. The experimental data from HiRes [25] (points in Fig. 1) refer to unknown primary particles; therefore, one usually compares the data with the two extremes (proton and iron) from simulations. Here we show results for EPOS 1.6 and QGSJET 01. The upper lines represent proton and the lower lines iron. Both models are compatible with the experimental data which seems to show a lightening of the primary cosmic ray composition between 10^{17} and 10^{18} eV.

A complementary observable is the muon number at ground, for example, expressed via the density $\rho_\mu(600)$ of muons per squared meter at a lateral distance of 600 m from the shower core (impact point). We show results from the MIA detector as a function of the primary energy in

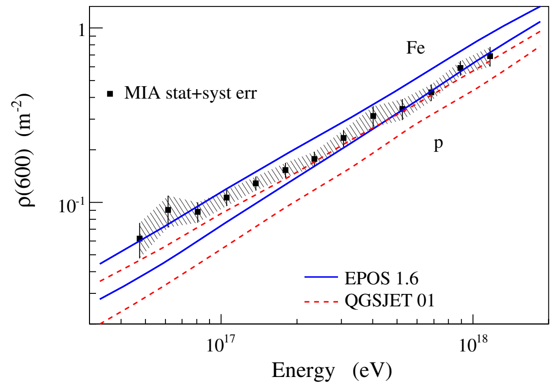

FIG. 2 (color online). The muon density $\rho_\mu(600)$ from the MIA experiment [7] (squares) as a function of the primary energy, compared to simulated proton and iron induced showers with EPOS 1.6 (full line) and QGSJET 01 (dashed line) as high energy hadronic interaction model.

Fig. 2, together with shower simulations for proton and iron from EPOS 1.6 and QGSJET 01, using the same notation as in Fig. 1. The HiRes-MIA data are—within the systematic errors—compatible with the EPOS results, showing a heavy primary composition at 10^{17} eV and a lighter one at 10^{18} eV. Compared to QGSJET 01, it is a shift of about 25% in the number of muons at ground.

So, for the first time, both the $\langle X_{max} \rangle$ and muon data are well in between the two extremes proton and iron, with a tendency towards lighter primaries at higher energies.

Not only the absolute value of the muon density has changed, but also the slope is slightly higher in EPOS 1.6 compared to QGSJET 01. This can be seen on a larger energy scale in Fig. 3: the number of muons arriving at ground divided by the primary energy in GeV is shown as a function of the primary energy between 10^{15} eV and 5×10^{20} eV. The EPOS curves are much flatter: at the lowest

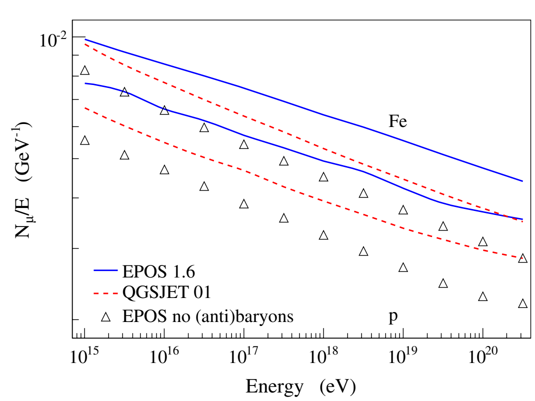

FIG. 3 (color online). Total number of muons at ground divided by the primary energy expressed in GeV, as a function of the primary energy, for proton and iron induced showers, using EPOS 1.6 (full lines) or QGSJET 01 (dashed lines) as high energy interaction model. The open symbols refer to EPOS without (anti) baryon production.

energy, the EPOS proton line is at most 15% higher than QGSJET, but at 10^{20} eV EPOS is more than 25% higher and gives even as much muons with a primary proton than QGSJET 01 for iron induced showers.

Comparing to KASCADE data, EPOS is in general compatible with the measurements, but it gives a too light average composition [26]. Current studies show that this seems to be due to the fact that in EPOS (and all other models) p-nucleus cross section is about 5% above the data and has a steeper slope at low energies [27]. A more consistent treatment of nuclear screening in an upcoming EPOS version will cure this problem. So EPOS gives finally similar results as QGSJET for KASCADE, however, with more muons and also more electrons (the effects cancelling each other roughly). For all detectors mainly based on a muon signal (MIA, AUGER,...), the mass composition results are quite different.

To obtain a deeper understanding of what makes the difference between EPOS and older models, one needs to have a closer look towards EAS physics. We observe not only more muons in air showers, when comparing EPOS and other models, also the number of baryons and anti-baryons—from here-on referred to as (anti) baryons—is increased. As a test, we modified EPOS parameters to suppress artificially the production of (anti) baryons in hadronic collisions, hence not reproducing accelerator data anymore. As a result, the number of muons is reduced on the average by 35%, as shown by open symbols in Fig. 3. At the same time, we see in Fig. 1 that the $\langle X_{max}\rangle$ remains unchanged. So we find that (anti)baryon production is a very efficient mechanism to affect the muon number without touching the $\langle X_{max}\rangle$.

As a cross check, we increase artificially the (anti) baryon production in the SIBYLL hadronic interaction model (commonly used for EAS simulations) by a factor of 2, keeping the total multiplicity constant. Then the number of muons increase by about 30% (not shown here).

In fact the correlation between the number of (anti) baryons (about 1% of the particles in the hadronic shower) and the number of muons in air showers has been shown at low energies in [28], but this was not considered to be an important issue in the modern hadronic interaction models designed for air shower simulations. For instance, we can see in Fig. 4 that QGSJET 01 (dashed line) is not able to reproduce the forward (anti) baryon production in π^+-*carbon* interactions as measured at 100 GeV lab [29], while it does reproduce the charge pion spectrum. EPOS which is designed for a more general purpose does both correctly.

Actually, thanks to a simple Heitler model generalized to hadronic showers [30,31], one can easily understand the role of the antibaryons in EAS. In this kind of toy model, a hadronic interaction of a charged particle with energy E will produce N_{tot} new particles with energy E/N_{tot}, with N_{EM} particles (π^0 mainly) transferring their energy to the

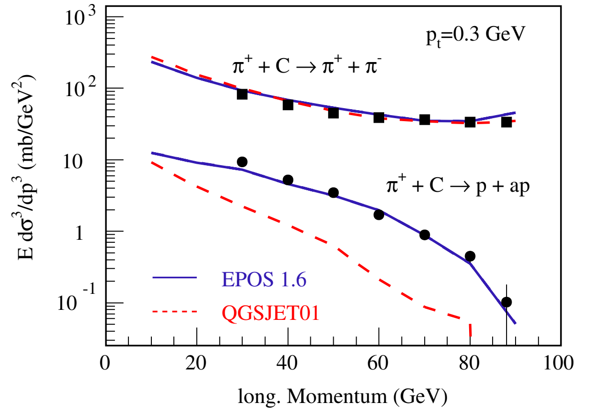

FIG. 4 (color online). Energy spectra of charged pions (top) and protons + antiprotons (bottom) for π^+-C interactions for EPOS 1.6 (full line) and for QGSJET 01 (dashed line) at 100 GeV total energy, compared to data (symbols) [29].

electromagnetic channel. Introducing a characteristic energy ($E_0 = 150$ GeV), where pions are assumed to decay into muons, the number of muons for a shower with primary energy E_0 after n generations is given as [32]

$$N_\mu = \{N_{tot} - N_{EM}\}^n = \left(\frac{E_0}{E_{dec}}\right)^{1+\ln R/\ln N_{tot}}, \qquad (1)$$

with $R = (N_{tot} - N_{EM})/N_{tot}$. The muon number depends therefore strongly on R, which is understandable since N_{EM} counts particles giving all their energy to the electromagnetic channel— not producing muons.

Usually these kind of toy models consider only pions as secondary particles, resulting in $R = 2/3$. In this case the muon number depends only on N_{tot}, as does X_{max} [32], as

$$X_{max} = \lambda_{had} + \lambda_{EM} \ln\left(\frac{E_0}{N_{tot}E_c}\right), \qquad (2)$$

with λ_{had} being the hadronic interaction path length, and with $E_c = 85$ MeV being the critical energy (where particles disappearing from the shower). So EAS simulations based on two different interaction models, producing different total multiplicities, should disagree for both X_{max} and muon numbers.

Now let us be more realistic, and consider all kinds of hadrons, including (anti)baryons. Now R is not simply 2/3, but it depends on the individual hadron yields, in particular, on the (anti) baryon production (being model dependent). With R being less than 1 and $N_{tot} \gg 1$, the muon number is very sensitive to the ratio R. As already pointed out and shown in Fig. 4, EPOS predicts much more (anti) baryons than QGSJET 01, corresponding to a larger R value, as shown Fig. 5 in p-air and π-air reactions at 10^5 GeV kinetic energy. With R being only slightly higher, the exponent in Eq. (1) is closer to one, increasing both the number of muons and the slope as a function of the energy, as observed Fig. 3.

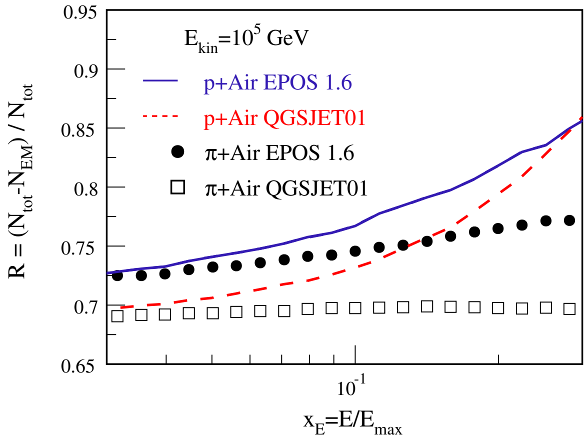

FIG. 5 (color online). The ratio $R = (N_{tot} - N_{EM})/N_{tot}$ versus the energy fraction for p-air interactions (full line for EPOS 1.6 and dashed line for QGSJET01) and for π-air interactions (dots for EPOS 1.6 and squares for QGSJET 01) at 10^5 GeV kinetic energy.

As a result, it is clear that changing the number of (anti) baryons affects R, but why is the effect so strong, knowing that the number of (anti) protons is quite small? The answer is given in Fig. 5: at large energy fraction x_E, where the produced particles contribute the most to the shower evolution, the ratio R is much bigger for p-air interactions than for π-air interactions (leading baryon effect). So more (anti)protons in one model compared to another (like EPOS compared to QGSJET), provide a larger R in a given generation. In addition, in the next generation, an enhanced number of p-air scatterings compared to π-air will enhance R even further, leaving more space to muons.

It should be said clearly that there are other features of interaction models which are very important for muon production, like, for example, the inelasticity. But they affect the $\langle X_{max}\rangle$ very strongly as well, contrary to the increased baryon production discussed in this Letter.

To summarize: simulating air showers by using the new high energy hadronic interaction model EPOS results in an increase of the muon density at 10^{18} eV of about 20% compared to QGSJET 01 calculations. So for the first time, both the $\langle X_{max}\rangle$ and muon data are compatible with a change of the average incident particle from heavy to light elements, in the energy range between 10^{17} and 10^{18} eV. It was shown that (anti) baryon production plays a much more important role in EAS physics than expected. An increased (anti) baryon production (in one model compared to another) increases the number of interactions where no leading π^0 is produced, more energy goes into hadronic subshowers, leading to more hadron generations, and finally to more muons. This mechanism does not depend on a particular hadronic interaction model. But it is fully efficient when using EPOS, which accounts better for (anti) baryon production than other models.

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