New facts about 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 seems to be impossible to accommodate at the same time the longitudinal development of air showers and the number of muons measured at ground. Using a new hadronic interaction model (EPOS) in air shower simulations produces considerably more muons, in agreement with results from the HiRes-MIA experiment. We find that this is mainly due to a better description of baryon-antibaryon production in hadronic interactions. This is a new aspect of air shower physics which has never been considered so far.

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Since more than ten years detailed extended air shower (EAS) simulations play 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 in AGASA array [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 shower each. The latter one is well under control (elementary processes of QED), whereas the hadronic interactions require models, being tested against accelerator data – 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 $X_{\text{max}}$) are relatively robust (less than 10% variations between models).

Using the currently employed hadronic interaction models (QGSJET01 [3], QGSJET II [4], SIBYLL 2.1 [5]), one has a tendency to have less muons in the simulations than observed by the experiments. Direct measurements of high energy muons (100 TeV) [6, 7, 8, 9] as well as experiments using low energy muons (1 GeV) like KASCADE [1] or HiRes-MIA [10], 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 using a purely experimental method or using a method based partly on the muon density at ground [11] and air shower simulations. The 25% difference could be explained by a lack of muons in the simulations. Many attempts have been made to force the models to increase the muon production without changing $X_{\text{max}}$ (well constrained by data) without success [12].

It should be noted that the number of muons predicted from shower simulations has important consequences on the astrophysical interpretation of the very high energy cosmic ray spectrum. If the muon number currently predicted is right, “new physics” has to be introduced to explain the observation of events beyond the “GZK-cutoff” [13] of $10^{20}$ eV, observed by the AGASA experiment (for a review see [14]).

In this work, we discuss the consequences of introducing the recently developed high energy hadronic interaction model EPOS into the air shower simulation models CORSIKA [15] and CONEX [16, 17, 18]. EPOS is a consistent quantum mechanical multiple scattering approach based on partons and strings [19], 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 [20]).

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 [21]. Motivated by the very nice data obtained by the RHIC experiments, nuclear effects related to CRONIN transverse momentum broadening [22], parton saturation, and screening have been introduced into EPOS [23]. Furthermore high density effects leading to collective behavior in heavy ion collisions are also taken into account [24]. It appears that EPOS does very well compared to RHIC data [25, 26], and also all other available data from high energy particle physic experiments (ISR,CDF and especially SPS experiments at CERN) [27]. As a result, it is the only model used both for EAS simulations and accelerator physics which is able to reproduce consistently almost all data from 100 GeV lab to 1.8 TeV center of mass energy, including antibaryons, multi-strange particles, ratios and pt distributions. It is intensively tested against data, but as explained, it is not a simple fit of data. And in particu-
lar, since this model is used for accelerator physics, many data are used to constrain the model parameters which are not a priori linked to cosmic rays and air showers.

For our analysis, CONEX and CORSIKA are used to simulate the air shower development, using GHEISHA \[28\] as low energy hadronic interaction model below 80 GeV. For the high energy interactions (above 80 GeV) EPOS 1.35 is used, and as a reference the most commonly used interaction model QGSJET01.

One of the most important observables in air shower physics is the distribution of 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 $X_{\text{max}}$ of this distribution is a function of the energy of the primary particle, as shown in Fig. 1 where the results represent averages over many showers. The experimental data from HiRes \[29\] (points in Fig. 1) refer to unknown primary particles, therefore one usually compares the data with the two extremes (protons and iron) from simulations. Here we show results for EPOS (full lines) and QGSJET01 (dotted lines).

The upper lines represent protons and the lower lines iron. Both models are compatible with experimental data which seems to show a lightening of the primary composition between $10^{17}$ eV and $10^{18}$ eV. But even at the lower energies, the average primary particle doesn’t seem to be heavier than a carbon nucleus as shown by the dashed line calculated with EPOS for carbon-induced showers. Above $10^{18}$ eV, data are well reproduced by proton induced shower.

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) as measured by the MIA \[10\] detector as a function of the primary energy, shown in Fig. 2 as triangles. Again we show shower simulations for protons and iron for EPOS and QGSJET01, using the same conventions as in Fig. 1. The HiRes-MIA data are now compatible with the EPOS results, using a heavier primary composition (but not too heavy, more like carbon) at $10^{17}$ eV and a lighter one (proton) at $10^{18}$ eV. Compared to QGSJET01, it is a shift of about 40% in the number of muons at ground. The proton line from EPOS lies exactly on the iron line from QGSJET01 (which was the model giving the highest number of muons before).

So for the first time, both $X_{\text{max}}$ and muon data are compatible with a change of the average incident particle from carbon to proton, between $10^{17}$ eV and $10^{18}$ eV.

Not only the absolute value of the muon density has changed but also the slope is slightly higher (less negative) in EPOS compared to QGSJET01. This can be seen on a larger energy scale 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 $10^{14}$ eV and $10^{21}$ eV. The EPOS curves are much flatter: at the lowest energy, the EPOS proton line is at most 25% higher than QGSJET, but at $10^{20}$ eV EPOS is a factor 2 higher and gives even more muons with a primary proton than QGSJET01 for iron induced showers. As a result, EPOS should be compatible with the KASCADE data. It will most probably give a lighter average composition, but a precise answer has to await full simulations (in preparation). However, EPOS will give very different results for the AUGER spectrum based on surface detector for instance compared to QGSJET01 simulations. In addition, EPOS has a slightly higher elongation rate (slope of $X_{\text{max}}$ as a function of primary energy) compared to QGSJET01 but stays fully compatible with the HiRes data at highest energies.
For a deeper understanding of what makes the difference between EPOS and older models, one has to have a closer look at the EAS physics. Looking at all particles produced in EAS by EPOS, we find that not only the number of muons is increased but also the number of baryons and antibaryons – referred to as (anti)baryons in the following. As a test, we modified EPOS parameters artificially to reduce the number of produced (anti)baryons by a factor of two, hence not reproducing hadrons artificially to reduce the number of produced particles re-interact with air after a constant interaction path length $\lambda_{\text{had}}$ and thus contribute to the hadronic cascade. In the electromagnetic shower, exactly 2 secondaries with equally shared energy are produced at each interaction, after a constant interaction path length $\lambda_{\text{EM}}$. Introducing a characteristic energy ($E_{\text{dec}} = 150$ GeV), where pions are assumed to decay into muons, the number of muons for a shower with primary energy $E_0$ can be written as

$$N_\mu = \{N_{\text{had}}\}^\alpha = \left(\frac{E_0}{E_{\text{dec}}}\right)^\alpha,$$

with $\alpha = \frac{\ln N_{\text{had}}}{\ln N_{\text{tot}}} < 1$, and where $n$ is the number of hadronic generations in the shower. Introducing $R = N_{\text{had}}/N_{\text{tot}}$, we have

$$\alpha = 1 + \frac{\ln R}{\ln N_{\text{tot}}}.$$

Eq. (2) shows that the muon number depends strongly on the ratio $R$ of the number hadrons initiating a hadronic sub-cascade to the total multiplicity, which is understandable since the difference between these two quantities are particles giving all their energy to the electromagnetic channel – not producing muons.

Usually these kind of toy models consider only pions as secondary particles. As a consequence, one has $R = 2/3$. So the muon number depends only on $N_{\text{tot}}$. The latter one affects as well $X_{\text{max}}$, since from our toy model we obtain

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

where $E_c = 85$ MeV is the critical energy (energy of the electromagnetic particles at the shower maximum in air and energy of particles disappearing from the shower). So EAS simulations based on two different interaction models, producing different total multiplicities, should disagree for both $X_{\text{max}}$ and muon numbers.

Let us now be more realistic, and consider all kinds of hadrons, including (anti)baryons. Particle production in hadronic interactions is model dependent, and so is the precise value of $R$. With $R$ being less than 1 and $N_{\text{tot}} >> 1$, the muon number depends very sensitively on the ratio $R$. One may imagine two interaction models with the same $N_{\text{tot}}$ but with more baryons in one model compared to the other, corresponding to smaller $N_{\text{EM}}$ and bigger $R$ values. With $R$ being even slightly higher, $\alpha$ is closer to one, increasing both the number of muons and the slope as a function of the energy as observed Fig. 8. This muon increase is also intuitively understandable: more baryons in one model compared to the other lead to a smaller $N_{\text{EM}}$, less energy is transferred to the electromagnetic component. There are more hadron generations and thus more muons are produced.

As a result, it is clear that variations of the number of baryons and antibaryons affect a shower, but why is the effect so strong although baryons and antibaryons represent only 1% of all hadrons. One should not forget that only hadrons with a large longitudinal momentum fraction $x_F$ (>0.1) contribute significantly to the cascade. Particle
yields at large $x_E$ are quite different from those at central rapidities, measured in accelerator experiments. Fig. 4 shows the energy spectra of $\pi^0$ produced in p-Air (dashed line) and $\pi^0$-Air (full line) reactions at $10^5$ GeV kinetic energy for EPOS. $\pi^0$'s produced in p-Air interactions are much softer than in $\pi^0$-Air simply because p-Air interactions do not produce leading $\pi^0$ whereas $\pi^0$-Air do so because of charge exchange. As a consequence, the ratio $R \approx 1 - N_{\pi^0}/N_{\text{tot}}$ for particles with more than 50% of the interaction energy is close to 15% for $\pi^0$-Air but about 1% for p-Air. In other words, producing only slightly more baryons per hadronic interaction in one model compared to another will decrease considerably the number of fast neutral pions ($\approx N_{\text{EM}}$) in the next generation, leaving more contributors to the hadronic cascade and providing thus more muons. It is worthwhile to say that having by any means more leading $\pi^0$, will decrease the number of muons and the slope as a function of the energy [24].

Why does the muon yield in EPOS differ so much from other models? As already said, EPOS has not been designed to be used for EAS simulations, but to understand hadronic interactions. Therefore all available data on p-p, p-A, A-A, $\pi$-p/A, K-p/A have been considered, in particular data on observables like (anti)baryons which so far have not been considered to be important for EAS simulations. Differences between hadronic interaction models used for EAS simulation will be discussed in detail in a forthcoming publication.

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 40% compared to QGSJET01 calculations. So for the first time, both $X_{\text{max}}$ and muon data are compatible with a change of the average incident particle from heavy to light element, in the energy range between $10^{17}$ eV and $10^{18}$ eV. It was shown for the first time 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 $\pi^0$ is produced, more energy goes into hadronic sub-showers, leading to more hadron generations, and finally to more muons.

The presented EPOS results have certainly to be confirmed by comparing to other air shower experiments (work in progress), but it seems already now that the Cosmic Ray energy spectrum based on EAS simulation will have to rescale its energy to lower values. Another consequence: since there is more energy in the hadronic part of the shower, the calorimetric energy measured by fluorescence detectors such as HiRes will correspond to a larger primary energy. The conversion factor is changed by about 5%. A more quantitative statement on the CR spectrum requires intensive simulations which will be presented soon.

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