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When heavy ions meet cosmic rays: potential impact of QGP formation on the muon puzzle

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The deficit of muons in the simulation of extensive air showers is a long-standing problem and the origin of large uncertainties in the reconstruction of the mass of the high energy primary cosmic rays. Hadronic interaction models, re-tuned after early LHC data, have a more consistent description of the muon content among them but still disagree with data. Collective hadronization due to the formation of a quark gluon plasma (QGP) has already been studied as a possible cause for a larger production of muons under extreme conditions (rare, very central nuclear interactions), but without real success. However, in the view of the most recent LHC data, a collective hadronization phase might not only be limited to such extreme conditions. And because of its different ratio of electromagnetic to hadronic energy, a QGP may have the properties to solve the muon puzzle. This hypothesis is demonstrated using a theoretical approach and tested in a proper way by the modification of hadronic model spectra in CONEX to mimic the production of a QGP also in less extreme conditions with a possible large impact on air shower physics.

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1. Introduction

Despite all the efforts made to take into account the first results of proton-proton collisions at the LHC in hadronic interaction models used for air-shower simulations, the observed number of muons, their height of production or even the depth of shower maximum are still not reproduced consistently by the models [1]. Furthermore, the differences in model predictions introduce uncertainty in cosmic ray data analysis which are less than in the past but still exceed the experimental uncertainty in certain cases [2]. But before claiming for the need for "new physics", it is important to guarantee that all the QCD standard physics is properly taken into account in these models. For that it is necessary to go beyond the simplest observables which are usually used to test them. The various LHC experiments provided a large amount of complex data to analyze and understand, in particular thanks to the correlation between different observables, which are not yet fully investigated.

Among the hadronic interaction models used for air-shower analysis, only EPOS LHC [3–6] includes all the features needed to have a detailed description of the correlation between various observables [1]. Indeed the core-corona approach in this model, which allows the production of a collective hadronization phase, appears to be a key element to reproduce LHC data. Before LHC, it was usually accepted that hydrodynamical phase expansion due to the formation of a quark-gluon plasma (QGP), for instance, was possible only in central heavy-ion collisions. Proton-nucleus (pA) collisions were then used as a reference to probe the effect of such collective behavior (final state) but with some nuclear effect at the initial state level, while proton-proton (pp) interactions were free of any nuclear effects. With the LHC operated in pp, pPb and PbPb mode, it is now possible to compare high-multiplicity pp or pPb events with low-multiplicity PbPb events (which correspond to the same number of particles measured at mid-rapidity) and surprisingly the very same phenomena are observed [7, 8] concerning the soft-particle production.

One of the most striking features observed in all systems is the long-range two-particle correlations and the evolution of the particle flow as described in [9]. In [10] the authors demonstrate how these data from the CMS Collaboration can be reproduced and explained using an approach combining standard perturbative calculations for initial conditions and hydrodynamical calculations for the final state interactions.

At the same time, the recent results compiled by the WHISP working group [11] clearly indicate that the discrepancy in the muon production between simulations and data, gradually increase with energy. It is a strong indication of a different hadronization than the one used in the current hadronic models [12–16], including EPOS LHC, which doesn't have enough core contribution according to data [7] published after the release of the model in 2012.

In [17], we present a modified version of EPOS LHC [4] based on EPOS3 [3] to study the consequence of the extended range of collective hadronization on air-shower physics in this particular model with positive results on the number of muons. To have a more general approach, new results based on modified secondary particle spectra following the core-corona approach applicable to any model are now presented.

In Section 2, we will discuss the impact of collective hadronization in the total number of muons produced by air showers. In Section 3 the basic principles the core-corona approach will be presented and we will discuss the changes made in CONEX [18] to take this modifications into account. Finally, in Section 4, we will discuss future developments.

2. Collective hadronization and Air-shower physics

The dominant mechanism for the production of muons in air showers is via the decay of light charged mesons. The vast majority of mesons are produced at the end of the hadron cascade after typically five to ten generations of hadronic interactions (depending on the energy and zenith angle of the cosmic ray). The energy carried by neutral pions, however, is directly fed to the electromagnetic shower component and is not available for further production of more mesons and subsequently muons. Thus, the energy carried by hadrons that are not neutral pions is typically able to produce more hadrons and ultimately muons in following interactions and decays. As explained in [12, 19], the ratio of the average electromagnetic to average hadronic energy, called R, and its dependence on center-of-mass energy, is thus related to the muon abundance in air showers: if this energy ratio is smaller (larger), more (less) energy is available for the production of muons at the end of the hadronic cascade and ultimately more (less) muons are produced. In fact it can even be demonstrated in the simple Matthews-Heitler model [20] that the exponent β of the energy dependence of the muon production is directly related to R as $\beta = 1 + \ln(1 - c)/\ln(N_{\text{all}})$ where N_{all} is the total multiplicity and $c = N_{\pi^0}/N_{\text{all}}$ and thus $R = c/(1 - c)$ if all particles have the same energy like in this simplified model.

Since in a collective hadronization (or statistical model) the production of particles with higher mass (in particular with strange quarks) [21] is not suppressed as in a string hadronization, the fraction of secondary pions in the dense core is reduced because many other more massive hadrons and resonances are produced. This leads to a lower ratio of the electromagnetic to hadronic energy density in particles produced from the core. As a consequence, such reduction of R due to more collectivity in secondary particle production should increase the slope β of the energy dependence of the muon production in air showers compare to traditional hadronic models where only the string hadronization is taken into account.

3. Core-corona effect

The discussion in the previous section suggests that a change of R is a potential way to reduce the discrepancy between measurements and air shower simulations. Nevertheless, R is quite well constrained by theory as well as laboratory measurements and, thus, can not be changed entirely arbitrarily as studied in an other analysis [22]. In a naive model like Ref. [20] where only pions are considered as secondary particles, $R = 0.5$. In a more realistic approach based on string fragmentation we have $R \approx 0.41 - 0.45$.

But as shown in Ref. [7], particle ratios such as K/π, p/π or Λ/π change with increasing secondary particle density, saturating to the value given by a thermal/statistical model with a freezeout temperature of 156.5 MeV [23] yielding $R \approx 0.34$. Such a behavior can be explained in terms of a core-corona picture [21]. This approach has been used in the framework of realistic simulations [24], but also in simple model calculations [25–28]. The basic idea is that some fraction of the volume of an event (or even a fraction of events) behaves as a quark gluon plasma and decays according to statistical hadronization (core), whereas the other part produces particles via string fragmentation (corona). The particle yield N_i for particle species i is then a sum of two contributions

$$N_i = \omega_{\text{core}}\, N_i^{\text{core}} + (1 - \omega_{\text{core}})\, N_i^{\text{corona}}, \tag{1}$$

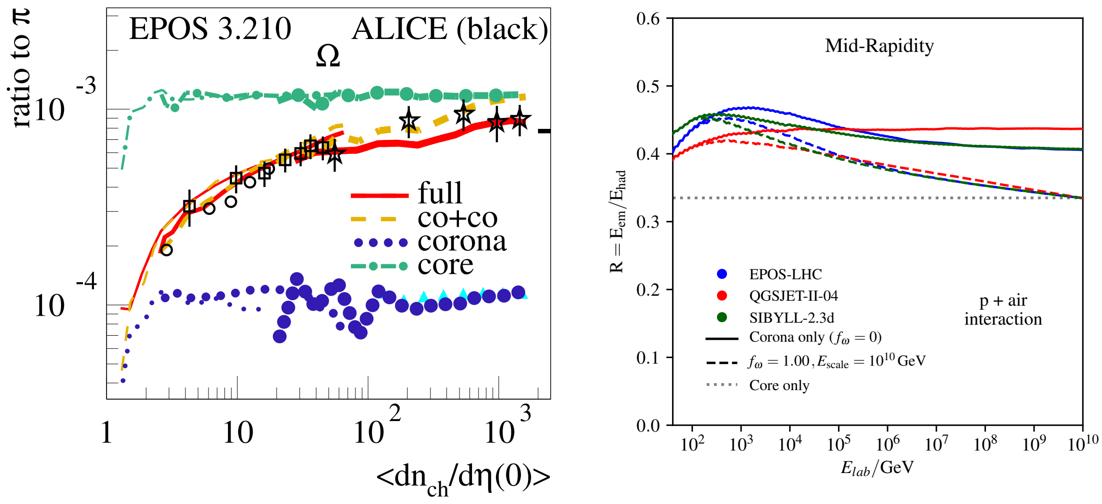

Figure 1: Left-hand side: Particle to pion ratio for the Ω baryon versus multiplicity at mid-rapidity, for different contributions (core (dash-dotted), corona (dotted), core+corona (dashed) and all (core+corona+hadronic gas) (full)) from the EPOS simulations, for different systems (pp (thin), pPb (normal), PbPb (bold)). We also plot ALICE data from [7]. Right-hand side: evolution of the ratio R from pure corona to pure core in case of linear increase of core fraction as a function of the logarithm of the energy for 3 different models in proton-air interactions at mid-rapidity.

where $N_i^{\rm core}$ represents statistical (grand canonical) particle production, and $N_i^{\rm corona}$ is the yield from string decay. Crucial is the core weight $\omega_{\rm core}$. In order to explain LHC data [7] the weight $\omega_{\rm core}$ needs to increase monotonically with the multiplicity, starting from zero for low multiplicity $p-p$ scattering, up to 0.5 or more for very high multiplicity $p-p$, reaching unity for central heavy ion collisions (PbPb) as illustrated in Fig. 1 using EPOS3 model [3].

In order to know whether such a constrained value of R could be low enough to increase the number of muons in air shower simulations such that the data could be reproduced, a simplified core-corona approach can be used to at least set some realistic upper-limit under the following assumptions :

- the fraction of core effectively increase with energy: the core-corona approach is originally as a function of the multiplicity and independent of the collision energy for a given multiplicity. Since the average multiplicity increase with the energy, the average core fraction must increase with energy.
- only the change in hadronization is taken into account: collective effects in core in principle includes particle correlations and flow, but since the longitudinal particle momentum is dominating over the transverse momentum down to relatively low energy, these effects can be neglected in first order.
- no nuclear effect is introduced: the multiplicity increase with the mass of the projectile, so the core fraction would increase for higher primary mass. This is not taken into account due to technical limitations (minimizing the effect for higher primary mass but only for the first few hadronic generations).

- core-corona effect is applied on full phase space: core hadronization has been observed at mid-rapidity, but in order to see the maximal effect on air shower to set an upper-limit, the modification should apply at larger rapidities.

So in the following, we are going to employ a straightforward core-corona approach, based on eq. (1), for any hadronic interaction model in CONEX air shower simulations. The particle yield from the chosen interaction model is by definition considered to be the corona yield, whereas we use the standard statistical hadronization (also referred to as resonance gas) for the core part. So $\omega_{\mathrm{core}} = 0$ would be the “normal" simulation with the default interaction model. Choosing $\omega_{\mathrm{core}} > 0$ amounts to mixing the yields from the interaction model according to the core-corona superposition shown in eq. (1) and depicted in Fig.. 1 right-hand side for proton-air interactions for 3 different hadronic interaction models EPOS LHC, QGSJETII.04 [29, 30] and SIBYLL 2.3d [31].

Technically, we directly modify individual particle ratios of the secondary particle spectra $\mathrm{d}N_i/\mathrm{d}E_j$, for particle species i and energy bins $\mathrm{d}E_j$, of hadronic interactions with air nuclei used by CONEX for numerical air shower simulations based on cascade equations. Knowing the initial ratios $\pi^0/\pi^\pm$, $p/\pi^\pm$, $K^\pm/\pi^\pm$, p/n, $K^0/K^\pm$ (taking into account strange baryon decays) from a corona type model and the value of the same ratios from the core model, we compute new spectra in which the particle yields include both, core and corona according to ω_{core}. Since the hadronization mechanism can affect only newly produced particles the properties of the leading particle should be preserved. To achieve that, the new particle yields are computed for all secondaries, but excluding the one corresponding to the respective projectile type, i.e. protons in proton-air, kaons in kaon-air interactions, and so on. The yield of the projectile-type particles is determined subsequently by exploiting energy conservation in all energy bins $\mathrm{d}E_j$ summed over all secondary particle species i: the sum $\sum_i E_j \mathrm{d}N_i/\mathrm{d}E_j$ must be conserved. Since at high $x_{\mathrm{F}} = E_{\mathrm{j}}/E_{\mathrm{lab}}$ only the projectile-type particles will have $\mathrm{d}N_i/\mathrm{d}E_j$ significantly different from zero (aka leading-particle effect), the resulting modified leading-particle type spectra at high x_{F} follow the original distribution, and are only affected by the scaling procedure at lower values of x_{F}. Together, this assures that energy conservation as well as the total multiplicity are not affected, but only the particle ratios. More details will be given in a future publication.

We expect the core weight ω_{core} to increase with energy in a logarithmic way like the total multiplicity. Thus, we use

$$\omega_{\mathrm{core}}(E_{\mathrm{lab}}) = f_\omega\, F(E_{\mathrm{lab}}; E_{\mathrm{th}}, E_{\mathrm{scale}}) \tag{2}$$

with

$$F(E_{\mathrm{lab}}; E_{\mathrm{th}}, E_{\mathrm{scale}}) = \frac{\log_{10}(E_{\mathrm{lab}}/E_{\mathrm{th}})}{\log_{10}(E_{\mathrm{scale}}/E_{\mathrm{th}})} \text{ for } E_{\mathrm{lab}} > E_{\mathrm{th}}, \tag{3}$$

to model this, starting already at fixed-target energies, $E_{\mathrm{th}} = 100\,\mathrm{GeV}$. Different energy dependencies are explored by changing E_{scale} from 100 GeV (corresponding to a step function), to 10^6 GeV, and 10^{10} GeV. The f_ω scale is varied from 0.25, 0.5, 0.75 to 1.0; in addition we enforce $F(E_{\mathrm{lab}}; E_{\mathrm{th}}, E_{\mathrm{scale}}) \stackrel{!}{=} 1$ for all $E_{\mathrm{lab}} \geq E_{\mathrm{scale}}$. This yields the ω_{core} energy dependencies as depicted in Fig. 2 left-hand side. All these scenarios have been used to simulate full air showers with CONEX, using cascade equations from the first interaction to the ground, for proton and iron primary particles at $E_0 = 10^{19}$ eV. In Fig. 2 the results are shown in the X_{max}-lnN_μ plane for QGSJETII.04. This typical example illustrate that it is well possible with modified hadronization in air shower cascades

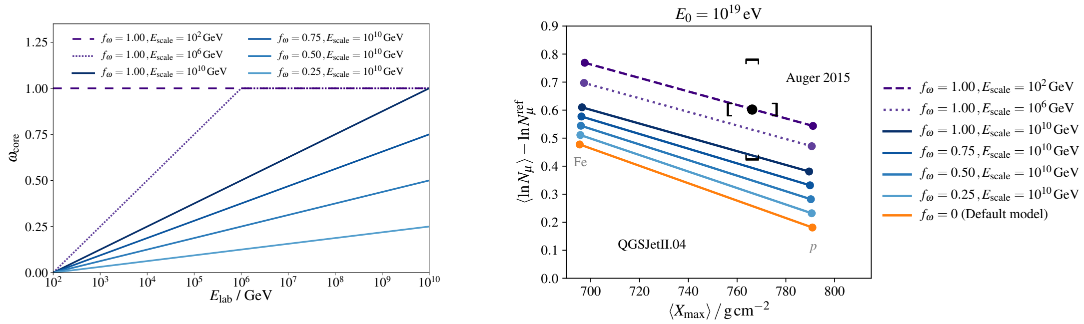

Figure 2: Left-hand side: Different energy evolutions probed for ω_{core}. The solid lines represent changing the scale f_ω of the effect, while the dashed lines also indicate the effect of changing E_{scale}. Right-hand side: Comparison of different core-corona mixing scenarios, as described in the text, on air shower simulations at 10^{19} eV QGSJETII.04 in the X_{max}-lnN_μ plane. The solid lines represent changing the scale f_ω, while the dashed lines also indicate the effect of changing E_{scale}. The *default* model corresponds to the corona-only simulations. The datum is from the Pierre Auger Observatory [32]. Each model line represents all values that can be obtained for any mixture of cosmic nuclei from proton (bottom right) to iron (top left).

to describe the data of the Pierre Auger Observatory. As expected, more core-like contributions are needed compared to what is currently provided by the models. This means, QGP-like effects also in light colliding systems and starting in central collisions at much lower center-of-mass energies may play a decisive role.

4. Summary

The better description of the collective hadronization and in particular the fact that the core is produced earlier than predicted by EPOS LHCcan have very important consequences for the muon production in air showers. The effect of QGP using the standard EPOS LHCwas shown not to be significant. Indeed in this model, the QGP was produced only for very high-multiplicity events and at mid-rapidity which are both rare and not so important for air-shower development. Other studies using a QGP or alternative hadronization as a possible new source of muons were all based on changes under extreme conditions too [13, 34] or with extreme consequences not observed at the LHC [14]. As shown here and in [33], according to the most recent LHC results, the collective hadronization happens at a much lower multiplicity and as a consequence with effects at larger rapidities (lower particle densities than foreseen). In that case, much more particles coming from the hadronization of a QGP play a significant role in the air-shower development. The production of the QGP is increasing with energy (since the multiplicity increases) leading to a reduce ratio R between energy going into electromagnetic particles and energy carried by hadronic particles and as a consequence the slope of the energy dependence of the muon production also increase with the primary energy and is closer to the one observed by the WHISP working group [11] in the data, and without changing the $\langle X_{max} \rangle$ too much. A stronger effect could be observed in case of nuclear projectile with could create a collective phase with a non zero chemical potential which could lead to an even stronger increase of the non electromagnetic secondary particles [16]. The combination of a mild increase like observed in this study with a proton primary with an even stronger effect for heavier projectile could be the complete solution of the muon deficit in air shower simulations. A monte-carlo model taking into account the core-corona effect in a detailed enough way to reproduce all major effects observed at the LHC is still under development [35]. More data in particular in forward phase space from LHCb [36, 37] or other projects [38] and using light ion beam light oxigen at the LHC is required to set further constraints on the core-corona mechanism.

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