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Through the Looking-Glass with ALICE into the Quark-Gluon Plasma: A New Test for Hadronic Interaction Models Used in Air Shower Simulations

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Recently, the ALICE Collaboration reported an enhancement of the yield ratio of strange and multi-strange hadrons to charged pions as a function of multiplicity at mid-rapidity in proton-proton, proton-lead, lead-lead, and xenon-xenon scattering. ALICE observations provide a strong indication that a quark-gluon plasma is partly formed in high multiplicity events of both small and large colliding systems. Motivated by ALICE's results, we propose a new test for hadronic interaction models used for analyzing ultra-high-energy-cosmic-ray (UHECR) collisions with air nuclei. The test is grounded in the almost equal column-energy density in UHECR-air collisions and lead-lead collisions at the LHC. We applied the test to post-LHC event generators describing hadronic phenomena of UHECR scattering and show that these QCD Monte Carlo-based codes must be retuned to accommodate the strangeness enhancement relative to pions observed in LHC data.

Besides addressing key questions in astrophysics, ultra-high-energy cosmic ray (UHECR) experiments provide unique access to particle physics at energies an order-of-magnitude higher center-of-mass energy than pp collisions at the Large Hadron Collider (LHC) [1]. However, a precise characterization of the particle physics properties is usually hampered by the ambiguity of model predictions computed through extrapolation of hadronic interaction models tuned to accommodate collider data. These predictions have sizable differences [2–4], even among modern (post-LHC) models [5], and quite often overlap with the phase of particle physics observables. Disentangling one from the other is of utmost importance to study particle physics in unexplored regions of the phase-space. The development of new approaches to reduce the systematic uncertainties of hadronic interaction models represents one of the most compelling challenges in UHECR data analysis. In this Letter we introduce a reliable technique for extrapolation into the ultra-high-energy domain.

QCD calculations on the Lattice [6] predict that under certain critical conditions of baryon number density and temperature, normal nuclear matter undergoes a phase transition to a deconfined state of quarks and gluons where chiral symmetry is restored [7]. For many purposes, such a quark-gluon plasma (QGP) can be described as a near-perfect fluid with surprisingly large entropy-density-to-viscosity ratio. Therefore, once formed, like any other hot object, the QGP transfers heat internally by radiation. Several phases can be identified during the QGP evolution. The initial state contains only gluons as well as valence u and d quarks, but strangeness is produced in the very early stages via hard (perturbative) $2 \to 2$ partonic scattering processes ($gg \to s\bar{s}$ and $q\bar{q} \to s\bar{s}$). Strangeness is also predominantly produced during the subsequent partonic evolution via gluon splittings ($g \to s\bar{s}$). This is because the very high baryochemical potential inhibits gluons from fragmenting into $u\bar{u}$ and $d\bar{d}$, and therefore they fragment predominantly into $s\bar{s}$ pairs [8]. In the hadronization process that follows this leads to the strong suppression of pions (and hence photons), but allows the production of heavy hadrons with high transverse momentum (p_T) carrying away strangeness. At low p_T non perturbative processes dominate the production of strange hadrons. Thus, the abundances of strange particles relative to pions provide a powerful discriminator to identify the QGP formation.

A QGP can be created by heating nuclear matter up to a temperature of 2×10^{12} K, which amounts to 175 MeV per particle. Relativistic heavy-ion collisions are then the best tool one has to search for QGP production. Recently, the ALICE Collaboration reported enhancement of the yield ratio of multi-strange hadrons to charged pions as a function of multiplicity at mid-rapidity in LHC proton-proton (pp), proton-lead (pPb), lead-lead (PbPb), and xenon-xenon (XeXe) collisions [9–12]. More concretely:

- the production rate of K^0_S, Λ, ϕ, Ξ, and Ω increases with multiplicity faster than that for charged particles;
- the higher the strangeness content of the hadron, the more pronounced is the increase;
- the ratios do not seem to depend on the system size or collision energies.

Altogether, this provides unambiguous evidence for the formation of a QGP in high multiplicity small and large colliding systems [14].

Now, if the QGP is formed in relativistic heavy-ions collisions one would also expect to be formed in the scattering of UHECRs in the upper atmosphere [15, 16]. Moreover, since the column-energy density in UHECR-air collisions is comparable to that in PbPb collisions at the LHC, the precise characterization of the QGP properties from ALICE data enables us to investigate QGP models describing the scattering of cosmic rays that impinge on the Earth's atmosphere with energy $10^9 \lesssim E/\mathrm{GeV} \lesssim 10^{11}$. Indeed, as we show herein ALICE data straightforwardly constrain these models without the need to rely on energy extrapolation.

Before proceeding, we pause to note that the column-energy density is the relevant parameter to compare QGP models with experimental data. This is because in the center-of-mass the particles are extremely Lorentz contracted so the time it takes to pass through each other is small compared to the time for signals to propagate transversely, and hence the pertinent parameter is the total *surface energy density*. The best way of getting this point across is to consider the collision of two nuclei of baryon number A_1 and A_2 in the center-of-mass frame. The energies per nucleon for each nucleus are written as $E_1 = \sqrt{s}/(2A_1)$ and $E_2 = \sqrt{s}/(2A_2)$, where s denotes the total center of mass energy squared. Approximating each nucleus in its rest-frame as a cube of side $L = A^{1/3}$ gives the surface energy density in GeV/nucleon-cross-section [17]

$$\Sigma = A_1^{1/3} E_1 + A_2^{1/3} E_2 = \frac{1}{2}\ \sqrt{s}\left(A_1^{-2/3} + A_2^{-2/3}\right). \qquad (1)$$

Finally, following the de-facto standard of high-energy physics, we rewrite (1) in the nucleon-nucleon center-of-mass frame

$$\Sigma = \frac{1}{4}\ \sqrt{s_{NN}}\ \left(A_1^{-2/3} + A_2^{-2/3}\right)\ (A_1 + A_2), \qquad (2)$$

where $\sqrt{s_{NN}} = 2\sqrt{s}/(A_1 + A_2)$ is the center-of-mass energy per nucleon.

For LHC PbPb scattering at $\sqrt{s_{NN}} = 5.02$ TeV we can use (2) to obtain

$$\Sigma_{\mathrm{LHC}}^{\mathrm{PbPb}} = 2.9 \times 10^4\ \mathrm{GeV}, \qquad (3)$$

whereas for LHC XeXe scattering at $\sqrt{s_{NN}} = 5.44$ TeV, we have

$$\Sigma_{\mathrm{LHC}}^{\mathrm{XeXe}} = 1.2 \times 10^4\ \mathrm{GeV}. \qquad (4)$$

This must be compared to UHECR protons colliding with air nuclei at $10^{10.5} \lesssim s/\mathrm{GeV}^2 \lesssim 10^{12.5}$, which leads to

$$9.8 \times 10^4 < \Sigma_{\mathrm{UHECR}}^{p\mathrm{air}}/\mathrm{GeV} < 9.8 \times 10^5, \qquad (5)$$

where we have taken $A_{\mathrm{air}} = 14$. For the same primary energy, if the UHECR is a nucleus instead of proton the column energy density is reduced. Now, using (1) it is straightforward to see that for helium and carbon nuclei with $E \gtrsim 10^9$ GeV, $\Sigma_{\mathrm{UHECR}}^{A\,\mathrm{air}} > \Sigma_{\mathrm{LHC}}^{\mathrm{PbPb}}$, but already for nitrogen (and of course nuclei with larger baryon number) there is a particular energy where $\Sigma_{\mathrm{UHECR}}^{A\,\mathrm{air}} \simeq \Sigma_{\mathrm{LHC}}^{\mathrm{PbPb}}$. For example, when a nitrogen with $E \simeq 10^9$ GeV collides with an air nucleus, we have $\sqrt{s_{NN}} \simeq 12$ TeV and a column-energy density $\Sigma_{\mathrm{UHECR}}^{\mathrm{N\,air}} \simeq 2.9 \times 10^4$ GeV, which is comparable to $\Sigma_{\mathrm{LHC}}^{\mathrm{PbPb}}$. Therefore, under the well justified assumptions of universality between different projectile/target combinations and approximate independence of the collision energy, we conjecture that the QGP model predictions of these two scattering processes must be roughly the same. In particular, both LHC PbPb scattering at $\sqrt{s_{NN}} = 5.02$ TeV and UHECR nitrogen-air collisions at $\sqrt{s_{NN}} \simeq 12$ TeV should produce the same hadron-to-pion yield ratios as a function of the charged multiplicity. The hadron-to-pion yield ratios as a function of the charged multiplicity observed in LHC PbPb scattering at $\sqrt{s_{NN}} = 5.02$ TeV have been reported by the ALICE Collaboration [9–12], providing a direct calibration for hadronic interaction models used for analyzing UHECR collisions with air nuclei.

TABLE I: Selected particle species α.

α	particles
π	$\pi^+ + \pi^-$
p	$p^+ + \bar{p}$
K	K_S^0
Λ	$\Lambda + \bar{\Lambda}$
Ξ	$\Xi^- + \bar{\Xi}^+$
Ω	$\Omega^- + \bar{\Omega}^+$

The column energy density is subject to large fluctuations from collision to collision. For fixed nucleon-nucleon center-of-mass energy, the multiplicity of charged secondary particles is expected to be a reasonable tracer of the column energy density. Large multiplicities correspond to many nucleons interacting (high density), small multiplicities to few nucleons participating in the collision (low density). Taking this argument into account one can perform a comparison of prediction to data as a function of charged particle multiplicity instead of the non-observable column energy density. Because charged multiplicity is a good tracer of the energy density in the collision, the particle ratios are expected to depend on whether the QGP is formed (or not) in the collisions. This is very well seen in the ALICE data [9–12]. High secondary multiplicities correspond to the formation of a larger QGP region than low-multiplicity interactions, as expected. Furthermore, the observed particle ratios are, to a first approximation, only depending on the charged particle multiplicity (in the considered energy range). They are similar for a given charged particle multiplicity and independent of the projectile-target combinations and different nucleon-nucleon center-of-mass energies. This can then be interpreted as reflecting the conjectured dependence on the column energy density.

We now turn to compare the predictions of post-LHC hadronic interaction models (QGSJET II-04 [18] , EPOS-LHC [19], and SIBYLL 2.3c [20, 21]) with the experimental data reported by the ALICE Collaboration [10]. We

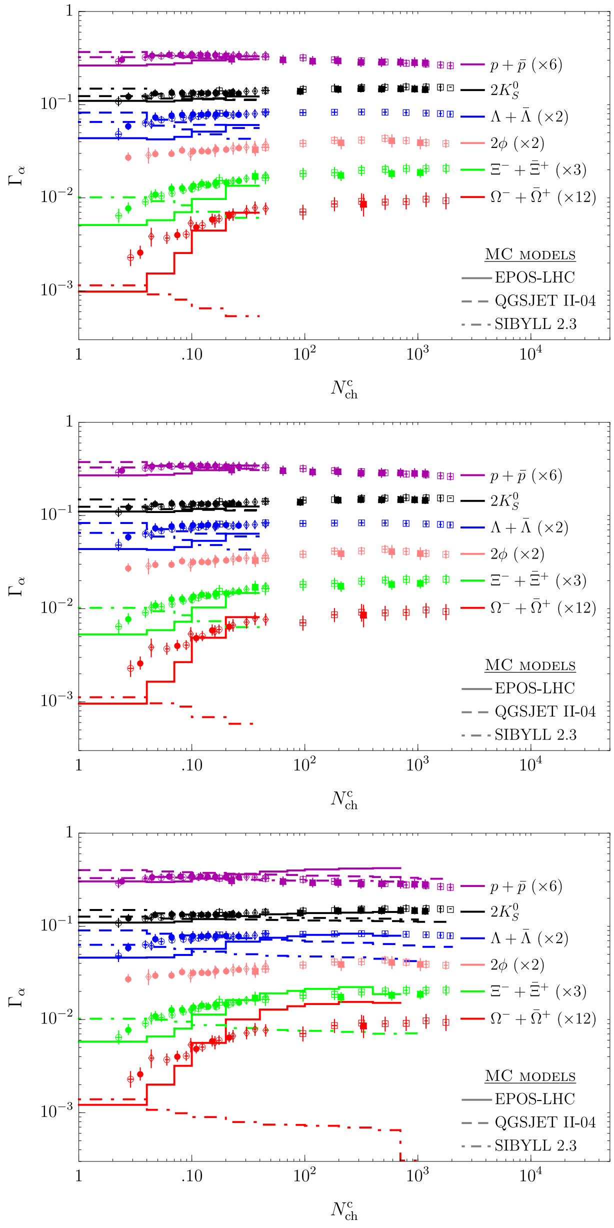

FIG. 1: Hadron-to-pion yield ratios as a function of the charged particle multiplicity in pp, pPb, PbPb, and XeXe collisions at the LHC. The predictions of post-LHC hadronic interaction models (top-to-bottom, pp $\sqrt{s} = 7$ TeV, pp $\sqrt{s} = 13$ TeV, NN $\sqrt{s_{NN}} = 12$ TeV) are compared to data reported by the ALICE Collaboration: ○ pp at $\sqrt{s} = 7$ TeV, ● pp $\sqrt{s} = 13$ TeV, ◇ pPb at $\sqrt{s_{NN}} = 5.02$ TeV, □ PbPb at $\sqrt{s_{NN}} = 5.02$ TeV, ■ XeXe at $\sqrt{s_{NN}} = 5.44$ TeV [10]. (We have corrected a factor of two which is missing in the labeling of $\Gamma_{\Lambda\bar{\Lambda}}$ in Fig. 6 of [10], Fig. 4 of [11], Fig. 1 of [12], and Fig. 1 of [13].)

run 10^6 collisions for each of the models, pair of primary particles, and center-of-mass energy. In analogy with the analyses presented by the ALICE Collaboration, we select those collisions containing at least one charged particle within the central ($|\eta| < 1$) pseudorapidity region. For those collisions, we first select the charged particles at midrapidity ($|\eta| < 0.5$). To estimate the observable $\langle dN_{\rm ch}/d\eta\rangle_{|\eta|<0.5}$, we write it as

$$\langle dN_{\rm ch}/d\eta\rangle_{|\eta|<0.5} = \frac{\int_{|\eta|<0.5} \frac{dN_{\rm ch}}{d\eta}\, d\eta}{\int_{|\eta|<0.5} d\eta} = N_{\rm ch}(|\eta| < 0.5) \equiv N^{\rm c}_{\rm ch}\,, \qquad (6)$$

the total number of charged particles at midrapidity which, for the i-th collision, is denoted by $N^{\rm c}_{{\rm ch},i}$. For this collision, we measure the total number of particles $N_{\alpha,i}$ of several groups of species α, as described in Table I. Armed with (6), we obtain the ratios to charged pions as

$$\Gamma_{\alpha,i} \equiv \frac{N_{\alpha,i}}{N_{\pi,i}}. \qquad (7)$$

In Fig. 1 we show the average ratios $\Gamma_\alpha \equiv \langle\Gamma_{\alpha,i}\rangle$ to all the collisions with the same $N^{\rm c}_{\rm ch}$ for the six species listed in Table I as reported by the ALICE Collaboration. For comparison, we also show the predictions of EPOS-LHC and SIBYLL 2.3c for the above mentioned species (other than ϕ) considering pp collisions $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV, as well as NN collisions at $\sqrt{s_{NN}} = 12$ TeV. We note, however, that the particles that play a role on the evolution of UHECR showers are pions, kaons, protons, neutrons, lambdas (and the corresponding antiparticles). For the simulations run with QGSJET, we only display predictions for the relevant secondaries driving the shower evolution. Overall, we conclude that none of the models correctly reproduce the main tendencies of ALICE data, especially for the description of multi-strange hadron production. For pp collisions, all hadronic interaction models seem to reproduce quite well $\Gamma_{p\bar{p}}$ and $\Gamma_{K^0_S}$, but fail to reproduce $\Gamma_{\Lambda\bar{\Lambda}}$. For NN collisions, EPOS-LHC reaches a good enough standard to pass the test in predicting the number of secondary kaons and lambdas as a function of the charge multiplicity. However, $\Gamma_{p\bar{p}}$ is overproduced by roughly 25%. SIBYLL 2.3c provides a good description of $\Gamma_{p\bar{p}}$, but fails to predict the number of kaons and lambdas. Finally, QGSJET slightly overproduces $\Gamma_{p\bar{p}}$ and fails to predict $\Gamma_{K^0_S}$ and $\Gamma_{\Lambda\bar{\Lambda}}$. All in all, EPOS-LHC provides the best description of the hadron-to-pion yield ratios as a function of the charged multiplicity relevant in the modelling of UHECR shower evolution. Of course, if QGP effects are correctly implemented in the models they should describe the aforementioned features as seen in data.

We end with three observations:

- Over the last year there has been a tremendous amount of progress in modeling UHECR interactions with EPOS-LHC [22]. In particular, the new EPOS-QGP has been properly tuned to reproduce the particle to pion ratio for the Ω baryon versus multiplicity at mid-rapidity as reported by the ALICE Collaboration [23, 24]. It will be interesting to see whether the EPOS-QGP predictions of NN collisions at $\sqrt{s_{NN}} = 12$ TeV can accurately match the experimental data of $\Gamma_{p\bar{p}}$.

- Future LHC data (including pO and OO collisions [25]) will provide new insights to guide software development.
- The formation of a QGP could play a significant role in the development of UHECR air-showers. In particular, the enhanced production of multi-strange hadrons in high-multiplicity small and large colliding systems would suppress the fraction of energy which is transferred to the electromagnetic shower-component. The formation of QGP blobs in air showers would then enhance the number of muons reaching ground level, and would also modify the shape of the muon density distribution $\rho_\mu(r)$. The curvature of this distribution ($d^2\rho_\mu/dr^2$) has been proposed as a possible discriminator between hadronic interaction models with sufficient statistics [26]. A thorough study of these phenomena is underway and will be presented elsewhere.

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