Snowmass2021 - Letter of Interest

Testing high-density QCD with ultra-high-energy cosmic ray air showers

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) EF06, EF07, NF05, NF06

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Abstract:

Our understanding of particle scattering has dramatically evolved in the last couple of decades. Since the first hints of QGP formation in heavy ion collisions at the end of last century, the idea that collisions at sufficiently large energies undergo a color-deconfined phase has gained acceptance. There is still a long way until we have confidence in our understanding of the different stages of these collisions: the initial conditions, the onset of the QGP and its evolution under the influence of a QCD equation of state, and its hadronization are still sources of uncertainty for the final observables. Accelerator experiments are not the only point of attack to solve these puzzles: the idea that QGP may be formed in UHECR air showers has recently gained momentum within the cosmic ray community, where it might come as a savior to solve the muon excess puzzle that Lund hadronization based models are having difficulties to address. In this letter we present some of these issues, and prepare the ground for the arrival of new computational tools of essential value.

Ultra-high-energy ($10^9 \lesssim E/\text{GeV} \lesssim 10^{11}$) cosmic ray (UHECR) collisions have center-of-mass energies ($50 \lesssim \sqrt{s}/\text{TeV} \lesssim 450$) well beyond those achieved at (wo)man-made colliders, and therefore provide an invaluable probe of the Standard Model (SM) of particle physics[1;2]. One of the current puzzles in our understanding of the SM lies in the formation of a thermal phase between the initial stages of a heavy-ion collision and the final hadronization into detectable particles. As the energy and mass of the incoming nuclei are increased, the maximum energy density reached during the interaction can easily surpass the typical energy density in a hadron, of about $1\ \text{GeV}/\text{fm}^3$. Under these circumstances, the quarks and gluons within the hadrons undergo a transition into a color deconfined, highly coupled, locally thermalized low viscosity fluid known as the Quark Gluon Plasma (QGP)[3]. An understanding of the properties of the QGP and its time evolution, as well as the preceding and subsequent stages during a collision, are fundamental to account for observables in UHECR-detection facilities and collider experiments[4].

Even though we are still far from understanding the full picture of this kind of events, there are observable effects that are agreeably associated with the formation of a QGP, such as: *(i)* suppression of hadron/jet yield due to energy loss of partons passing through the formed QGP medium (jet quenching)[5;6], *(ii)* thermal enhancement of strange quarks[7;8], *(iii)* azimuthal anisotropies (elliptic flow)[9;10], *(iv)* enhancement of low-p_T photon yield[11]. Various proposed signatures of QGP have been observed in AuAu collisions at RHIC and in PbPb collisions at the LHC[12–22]. The most recent and perhaps most intriguing evidence for QGP formation emerged in ALICE observations, which show an enhancement of the yield ratio of strange and multi-strange hadrons to charged pions as a function of multiplicity at mid-rapidity not only in PbPb and XeXe collisions but also in pp and pPb scattering[21;23].

One of the uncertainties in our description of this type of events stems from the lack of understanding of the initial state which later evolves to a locally thermalized QGP. An accepted model of the initial conditions in heavy-ion collisions consists in the formation of macroscopic color fields from the coherent behavior of low x gluons, as their transverse sizes grow enough to make them overlap with each other. This idea is referred to as the Color Glass Condensate (CGC)[24;25]. Models implementing this idea, such as the IP-Glasma model[26] or the KLN model[27] can provide realizations of the initial conditions. The evolution to a phase where hydrodynamics is applicable is not yet understood. Alternatives to coherent models like the CGC might consider the collective effects of individual semi-hard parton collisions within pQCD as a way to produce minijets which could be considered as the initial state for the QGP[28;29], among other possibilities. Both types of models are supposed to account for the large production of entropy, expected to occur in the early stages of heavy-ion collisions. After the early stages that fix the initial conditions, the system evolves into a locally equilibrated plasma. This process, not currently understood for the coherent initial conditions, can be understood through kinetic theory for the incoherent ones. In the regime after this pre-thermalization stage, (viscous) hydrodynamics drives the evolution of the QGP, in which lattice calculations are required to provide a parametrization of the equation of state[30]. Finally, the effect of a collective statistical hadronization in addition to the expected string fragmentation opens new venues for model builders[31].

Despite the many gaps in our current description of heavy-ion collisions, experimental efforts are providing ever deeper insights into them. The Cosmic Ray community has a long history of contributions to the High Energy Physics field. The highest energy cosmic rays currently observed by the Pierre Auger Observatory (Auger)[32;33] and the Telescope Array (TA)[34] show a significant discrepancy in the shower muon content when compared to predictions of LHC-tuned hadronic event generators[35]. Since the predicted muon component rises with energy, one may well argue that if the energy is under-estimated, that can entirely explain the so-called "muon puzzle." Indeed, from the spectrum analysis in the common declination band we know that in the energy range where the discrepancy has been observed there is a $\sim 15\%$ difference in energy scale between Auger and TA, which is even higher at highest energies[36]. However, any concern about energy calibration has been addressed in the combined analysis of Auger hybrid measurements by looking at the zenith-angle dependence, so that the effects of energy calibration and muon excess could be disentangled[33]. More recently, Auger findings have been confirmed studying air shower measurements over a wide range of energies. The muon excess starts at $E \sim 10^8$ GeV, increasing with a slope which was found to be significant at about 8σ[37;38] when considering the hadronic event generators EPOS-LHC[39] and QGSJet-II.04[40]. The muon puzzle and the intriguing ALICE measurements provide a new example of the UHECR $\leftrightharpoons$ collider synergy, because the almost equal column-energy density in UHECR-air collisions and LHC PbPb scattering[41] allows for a direct tests of next-generation QGP event generators[42].

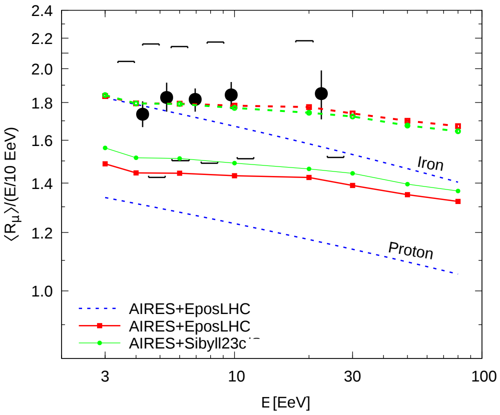

Figure 1: Auger data with statistical (ϕ) and systematic (▭) uncertainties[32]. The colored lines show estimations of $R_\mu^{\rm MC}$ from AIRES[43] simulations in three scenarios: EPOS LHC/single composition (blue), EPOS LHC/mixed composition (red), and Sibyll 2.3c[44]/mixed composition (green). A constant shift is added to the solid red/green lines to match the data better (red/green dashed lines). Taken from[45].

Explaining the muon puzzle is made more challenging by the measurements of the distribution of the depth of shower maximum, $X_{\rm max}$, and the fluctuations in the number of muons[46]. A thorough phenomenological study has shown that an unrivaled solution to the muon deficit, compatible with the observed $X_{\rm max}$ distributions, is to reduce the transfer of energy from the hadronic shower into the electromagnetic shower, by reducing the production or decay of neutral pions[47]. Several models have been proposed to accommodate this effect, including those of particular interest here wherein strangeness production suppresses the pion-to-kaon ratio[47–52]. In Fig. 1 we show a comparison between Monte Carlo (MC) simulations and data[45]. The simulations have been carried out considering an inclination from the vertical of 67°. For each set of showers, the ratio $R_\mu^{\rm MC} = N_\mu^{\rm MC}/N_{\rm Ref}$ (which can be directly compared with data) has been evaluated considering the average number of muons at ground level, with $E_\mu > 300$ MeV and taking $N_\mu^{\rm Ref} = 1.455 \times 10^7$[32]. The UHECR admixture follows Auger results on nuclear composition[53]. Altogether, we see that the combination of a mix nuclear composition with the Chiral Symmetry Restoration re-scaling entertained in[47] can accommodate the muon discrepancy. An interesting idea which has not yet been included in the UHECR simulations is the consideration of stabilized strange quark matter[54;55]. Searches will be carried out by mini-EUSO[56] and POEMMA[57].

Besides the potential that QGP effects on cosmic ray showers might have to solve the muon problem, the richness of phenomena observed in these events is worth studying on its own right. The QGP effects in collisions described above together with forward signatures unaccessible to particle accelerators might be accessible through cosmic ray observatories. This would create a new opportunity for the CR community to provide results useful in accelerator physics and cosmology, where the QGP also plays a fundamental role.

The path towards these kind of analyses relies heavily on the availability of computational power and its efficient use, a quickly evolving area where parallel and GPU computing and modular programming in modern languages are proving essential. In this line, the re-developement of widely used FORTRAN based tools like CORSIKA[58] or HIJING[59] into their new C++/Python forms CORSIKA 8[60;61] and HIJING++[62] may pave the way for a new era in CR physics simulations where the implementations of new/modified models like the ones considered here is easily supported. The implementation of HIJING++ with CR-borne tools like AIRES and CORSIKA can bring a new valuable player into the hadronic models game for QGP exploration and complement the efforts put on EPOS[31;63]. In addition, future data from the LHC in the fixed-target mode[64] from LHCb[65] or ALICE[66], from LHCf[67], from FMS[68], and from FASER[69] will provide invaluable information to address the muon problem and its possible QGP connection.

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