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Muon Puzzle: Bridging the gap between cosmic ray and accelerator experiments

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Multiple cosmic ray experiments have observed that the various high-energy physics models are unable to explain the muon multiplicities at very high primary energies. The models consistently predict lower numbers as compared to what is experimentally observed. This is termed as the "*muon puzzle*", as model tuning cannot resolve this issue. A possible solution proposed is the formation of quark-gluon plasma which invariantly produce more strange particles that decays into muons. We explore the electromagnetic to hadronic energy fraction in the final state particles and compare it with the strangeness production over different systems and energies used at the Large Hadron Collider using various models like EPOS LHC, SYBILL 2.3d, QGSJET II-04 and PYTHIA. The results will be presented with an outlook in view of the recently proposed OO and pO collisions at LHC.

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1. Introduction

When primary Ultra-High Energy Cosmic Rays (UHECRs) traverse the Earth's atmosphere, they interact with atomic nuclei, initiating a cascade of complex processes. These interactions produce a multitude of secondary particles, which subsequently interact with atmospheric nuclei or decay, depending on their respective energy thresholds. Consequently, a shower of particles, known as an Extensive Air Shower (EAS), is formed, extending over a vast spatial area. These UHECRs offer a unique and promising avenue for studying particle physics phenomena that remain largely inaccessible within the confines of accelerator facilities such as the Large Hadron Collider (LHC) [1]. They provide a distinctive opportunity to explore centre-of-mass energies and kinematic regions that are otherwise unattainable, enabling researchers to probe the fundamental properties of particles and interactions under extreme conditions. Ground-based experiments conduct extensive measurements of EAS to comprehend the nature and origin of these cosmic rays. Among the various parameters investigated, a particularly intriguing aspect is determining the cosmic ray mass composition as a function of the primary energy. This investigation is primarily reliant on two crucial characteristics of the showers: (a) the depth at which the shower reaches its maximum development, denoted as X_{max}, and (b) the number of muons generated within the shower, represented by N_μ [2, 3]. These features serve as essential indicators for inferring the composition of the primary cosmic rays. However, achieving precise and accurate determination of the mass composition is, at present, a significant challenge due to the inherent uncertainties associated with the modelling of these shower characteristics. Existing models rely on extrapolations from hadronic interaction models, calibrated and tuned to describe collider data. Nevertheless, when applied to the extreme energies and conditions of UHECRs, these models introduce uncertainties, with different models giving different results, thereby limiting the precise determination of the mass composition.

Lattice QCD calculations have predicted a phase transition from hadronic matter to a deconfined QCD matter under extreme conditions, i.e. high energy and/or number densities. The signatures of the deconfined state of partons, consisting of quarks and gluons, have been experimentally observed in ultra-relativistic collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). These collisions have provided an ideal environment for creating and studying a thermally equilibrated phase of Quantum Chromodynamics (QCD), known as the quark-gluon plasma (QGP). Interestingly, it is found that the surface-energy densities in collisions involving high-energy cosmic rays and air nuclei can be comparable to or even higher than the energy densities observed in lead-lead (Pb-Pb) collisions at the LHC [4]. This suggests that the formation of a deconfined phase, similar to the QGP, cannot be ruled out in interactions of high-energy cosmic rays with air nuclei. Such interactions may lead to the creation of a transient QGP-like state at extreme energy densities. In relativistic nuclear collision experiments, strangeness enhancement has been widely recognized as a key signature of QGP formation [5, 6]. Strangeness enhancement refers to the increased production of strange quarks and their associated hadrons, such as kaons and hyperons. The observation of enhanced strangeness production in heavy-ion collisions has provided strong evidence for the existence of the QGP. Surprisingly, recent experiments conducted by the ALICE collaboration have shown that even in small systems, such as proton-proton (pp) collisions, there is evidence of strangeness enhancement [7]. This unexpected observation suggests that the conditions necessary for QGP formation can manifest in a wide range of collision systems.

Furthermore, experimental findings of strangeness production in pp collisions have revealed an intriguing inverse relationship between strangeness enhancement and the energy deposited in the zero degree calorimeter (ZDC), usually used to measure the spectator energy. This finding implies that the formation of a QCD medium, which aids strangeness production, depends significantly on the energy deposited at the collision vertex [8]. Therefore, in high-energy cosmic ray interactions with the Earth's atmosphere, the energy available for particle production and subsequent shower development plays a vital role in determining the possibility of QGP formation. To better understand the dynamics of high-energy cosmic ray interactions and their relationship to QGP formation, simulations using the CORSIKA air shower package can be employed. Such investigations have revealed that the strangeness component increases with primary energy and decreases with increasing distance from the interaction vertex due to particle decays [9]. This finding suggests that as the energy of primary cosmic rays increases, the energy transferred from the hadronic cascade to the electromagnetic cascade, through processes such as $\pi^0 \rightarrow 2\gamma$ decay, decreases. Consequently, more energy is retained in the hadronic component, increasing muon multiplicities at the ground level due to meson decay.

In summary, investigations into the possibility of QGP formation in high-energy cosmic ray interactions with air nuclei have shed light on the intriguing physics underlying these extreme collision processes. The observed strangeness enhancement in relativistic nuclear collisions and small systems provides valuable insights into high-energy particle interaction dynamics. Further exploration of the relationship between strangeness production, electromagnetic and hadronic energy fractions, and shower development can deepen our understanding of UHECR-air interactions. In present work [10], the increase of strangeness in cosmic ray interactions within the Earth's atmosphere has been proposed as a potential solution to the muon puzzle [11–14], a longstanding mystery regarding the excess of muons observed at the ground level.

2. Methodology

Particle production in ultra-relativistic heavy ion collisions is studied using perturbative and/or non-perturbative Quantum Chromodynamic (QCD) methods. Several models successfully explain experimental data and are selected for testing in this work, including updated versions of cosmic ray interaction models and models tailored for accelerators. These models are applied to various collision species and the centre of mass collision energies. The EPOS LHC [15], QGSJET II-04 [16], and SYBILL 2.3d [17] models are provided within the Cosmic Ray Monte Carlo Package, CRMC (v2.0.1)[18], while the PYTHIA 8 [19, 20] tunes use version PYTHIA 8305.

The models mentioned above are further used to understand the energy distribution among electromagnetic particles in hadronic collisions through R-factor given as [10, 21, 22]:

$$R(\eta) = \frac{\langle dE_{em}/d\eta \rangle}{\langle dE_{had}/d\eta \rangle} \tag{1}$$

Here, $\langle dE_{em}/d\eta\rangle$ denotes the average energy carried by photons and $e^{\pm}$, while $\langle dE_{had}/d\eta\rangle$ represents the average energy summed over all hadrons in pseudorapidity bins, η. This quantity relates to the hadronization mechanism followed by the partonic system. A system with high energy density typically undergoes statistical hadronization, favouring the production of heavier hadrons. Consequently, the production of charged hadrons exceeds that of π^0 mesons, resulting in a reduced energy loss to the electromagnetic cascade.

For pp, p-O, and p-Pb collisions, one million events are generated, while for the Pb-Pb system at corresponding energies, 500 thousand events are generated. The calculations consider a pseudorapidity range of $|\eta| < 2.0$ for all systems following the ALICE experiment [23]. The ALICE experiment [23] defines the final state particles using the $c\tau$ definition. These particles are then used to measure the R factor and strangeness (K/π) as a function of charged particle multiplicity in the collision.

3. Results and Discussion

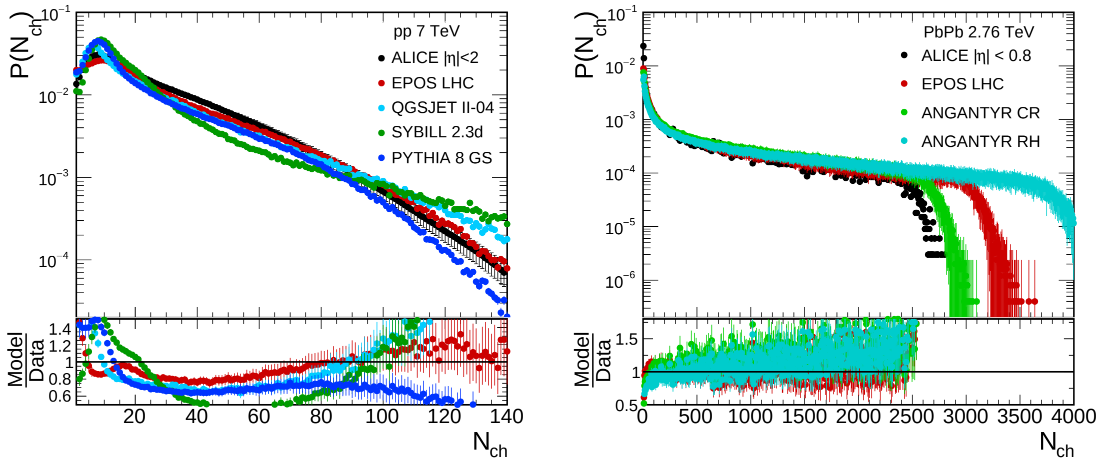

Figure 1: (Color online) Left panel: Comparison of charged-particle multiplicity distributions obtained from various models with ALICE experimental data for pp collisions at $\sqrt{s}$ = 7 TeV [23]. The ratio of simulated and experimental data is shown in the bottom left panel. Right panel: Model comparison of charged-particle multiplicity distributions for Pb-Pb collisions at $\sqrt{s}$ = 2.76 TeV with ALICE experimental data [24] with the lower panel showing the ratio between them. The error bars in the data points are the statistical uncertainties [10].

The validity and applicability of the chosen models are checked initially by comparing the charge particle distribution of the ALICE data [23, 24] with the model calculations with the same kinematic cuts employed in data. This comparison is shown in Fig.1 where the left panel compares the results from EPOS LHC, SYBILL 2.3d, QGSJET II-04 and PYTHIA colour reconnection (gluon splitting mode) models with $\sqrt{s_{NN}}$ = 7 TeV pp collisions at ALICE. It is observed that a reasonably good agreement is obtained by all the models, with the EPOS LHC model giving the best results. A similar exercise is done for the heavy-ion system (Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV) also by using the EPOS LHC and the ANGANTYR mode in PYTHIA. It is observed that the PYTHIA ANGANTYR model with colour reconnection gives the best description of the dataset. With this "quality assurance" study hinting at the applicability of the models, we further go ahead by dividing the generated dataset into ten equal multiplicity (centrality) classes.

Strangeness production in the various models is studied through the multiplicity dependence of the kaon to pion (K/π) ratio. It is observed in Fig.2 that the general trend of increasing K/π ratio seen in data [25] is followed only by the EPOS LHC model. The QGSJET II-04 model shows that the K/π ratio remains constant over increasing multiplicities, while the SYBILL 2.3d and PYTHIA GS models show a decreasing trend at low multiplicities. The PYTHIA ANGANTYR models remain well below all the other models with only minor variations with multiplicity. This indicates the importance of the core-corona picture used in EPOS LHC in explaining the strangeness enhancement observed in experiments.

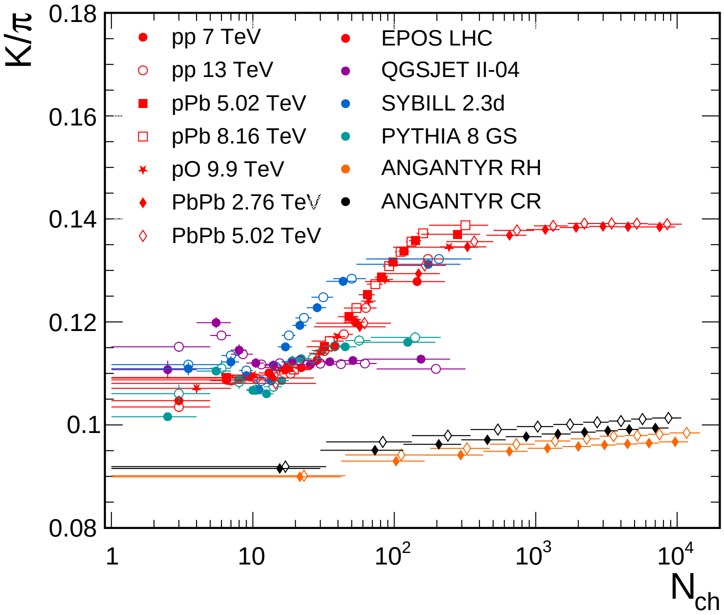

Figure 2: (Color Online) Kaon to pion meson ratio with mean charged particle multiplicity obtained from multiple models across various colliding species and centre of mass energies [10].

The development of an EAS involves collisions over large distances from the initial interaction point. Also, much of the particles produced either decay or get absorbed in the atmosphere. Thus, conventional signatures used in colliders might not be sufficient in the case of UHECR-air interactions. Proper consideration of the electromagnetic and hadronic energy fractions in simulations is thus critical in understanding the air shower development. An increase of strange particle production, as observed in Fig.2, would indicate a decrease of R defined in Eq.1. A decrease of R in UHECR-air interactions may thus be considered a signature of strangeness enhancement and thermalization. In Fig.3, we explore the dependence of R on charged-particle multiplicity. It is seen that the EPOS LHC model shows a continuous decrease of R with multiplicity, which may be correlated with the increase of K/π ratio observed in Fig.2. The QGSJET II-04 and PYTHIA models show that the electromagnetic to hadronic energy fraction remains almost constant with multiplicity. The ANGANTYR tunes being the most deviating from the other models show that the change of tunes does not significantly affect R. The SYBILL 2.3d model shows a non-monotonic nature with R initially decreasing and increasing at higher multiplicity.

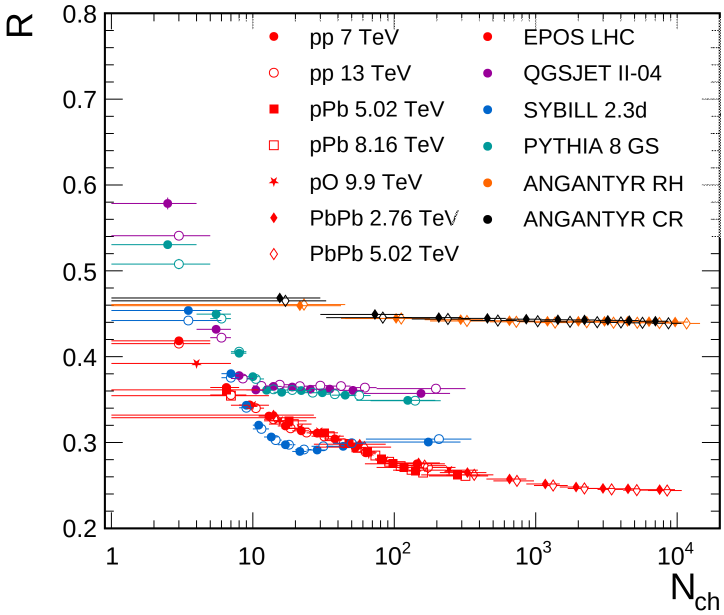

Figure 3: (Color Online) R as a function of charged particle multiplicity considering simulated data from multiple models across various colliding species and centre of mass energies [10].

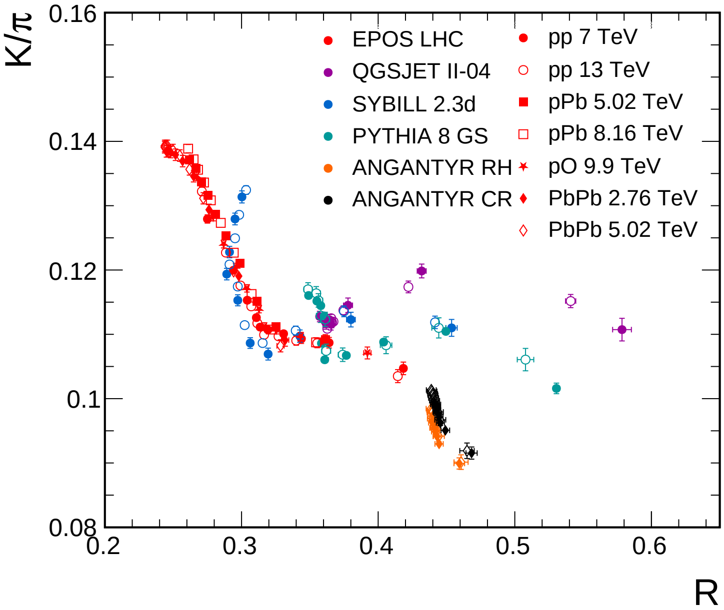

Figure 4: (Color online) Correlation between K/π ratio and R obtained using the different models [10].

Figs.2 and 3 show the multiplicity dependence of K/π and R, respectively, showing opposite trends. Thus, looking at the correlation between these two quantities would be informative to understand them better. Also, studying the multiplicity dependence of the correlation would help in giving predictions and give the relevant multiplicity range of interest to the study of R in colliders like the LHC. With these goals in mind, we have performed a correlation study of these parameters as shown in Fig.4. It is observed that the EPOS LHC model follows a negative correlation between these quantities in the multiplicity range of $N_{ch} = 10 - 200$. Beyond these limits, the linear correlation breaks down. This correlation is relevant for all systems from pp to Pb-Pb through p-O and p-Pb, as seen in Fig.4. Also observed is that the other models considered in our study do not follow this correlation.

4. Conclusion

In this work, we have explored a possible solution to the muon puzzle by considering the possible formation of a thermalized medium in UHECR-air interactions. We have discussed the importance of introducing new observables, which may be necessary for such interactions. The multiplicity dependence of one such observable, R, is also explored in this study. We have also tried to correlate the strangeness production with R, thereby observing the effect of strangeness production on the energy division between daughter particles, which finally affects the muon production. We have observed a decrease of R with increasing strangeness in the multiplicity range given by $10 < N_{ch} < 200$, which might be of interest in further studies of this factor in collider experiments. The detailed study and review of these parameters is given in Ref. [10].

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