PROCEEDINGS OF SCIENCE

PoS(ICRC2025)1417

The impact of accelerator data on our understanding of extensive air showers

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Before the start of CERN in 1954, cosmic rays (CR) were the main source of high energy particles leading to the discovery of anti-matter, muons and first mesons. Then particle accelerators provided controlled environments for studying high-energy particle interactions, producing precise data leading to the development of the Standard Model. These data were used early-on to create models to study extensive air showers (EAS), complex particle cascades initiated by high-energy cosmic rays, but its only in the late 90's that both EAS models and experiments became precise enough to start to see discrepancies between hadronic model predictions and EAS data. Problems like "the muon puzzle", characterized by an unexpected surplus of muons in cosmic ray showers, has propelled further investigations into particle interactions. This talk will discuss how accelerator data have improved the accuracy of EAS models, resolved discrepancies, and offered new insights into hadronic interactions. We will also address the challenges and future directions in integrating accelerator data with EAS observations, underscoring the importance of taking into account all type of colliding system. From the simplest electron-positron annihilation to the most complex Lead-Lead or the newest proton-Oxygen interactions, we need them all to resolve the remaining inconsistencies in the models and finally improve the predictions for Astroparticle physics.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

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[*] Speaker

1. Introduction

Cosmic rays are high-energy particles that constantly bombard the Earth's atmosphere from all directions in space. They consist primarily of protons (about 90% at low energy) and fully ionized atomic nuclei (dominating at the highest energies), with a small fraction of electrons and other particles [1]. The energy spectrum of cosmic rays spans over more than ten orders of magnitude, from 10^9 eV to beyond 10^{20} eV, and understanding the origin and properties of these energetic particles is one of the most intriguing challenges in astrophysics.

When (ultra) high energy cosmic rays ((U)HECR) enter the Earth's atmosphere, they interact with atmospheric nuclei, initiating a cascade of secondary particles known as an extensive air shower (EAS). These showers eventually produce stable photons and electrons, which can be detected in the atmosphere and at ground level. In addition, muons have a long enough life time to be detected at ground level. The muons, being produced after a long chain of hadronic interactions, carry information about the entire hadronic cascade. In addition, some hadrons, mostly nucleons but also mesons, can reach the ground. Before the advent of powerful particle accelerators, scientists relied on cosmic rays as a natural source of high-energy collisions. In the 1930s and 1940s, researchers used cloud chambers and photographic emulsions placed at high altitudes or on mountaintops to detect these byproducts of cosmic ray interactions with Earth's atmosphere. These experiments led to the discovery of several unexpected particles, including the positron (the antimatter counterpart of the electron) in 1932 and the muon in 1936, both of which were not predicted by existing theories at the time. Most notably, in 1947, the pi meson (pion) and the kaon were identified in cosmic ray data, revealing new types of interactions and paving the way for the development of the quark model and the broader field of particle physics.

It is only once the hadron production started to be understood from accelerator data from the 1960s to 1980s that EAS became a tool to study the origin of the primary cosmic ray, but still with limited interpretation due to limited computing resources. The development of air showers is sensitive to the mass of the primary cosmic ray, with heavier nuclei producing showers that develop higher in the atmosphere and contain more muons compared to showers initiated by protons [6]. The mass composition of cosmic rays plays a pivotal role in astrophysical models, influencing our understanding of cosmic ray acceleration mechanisms, propagation through interstellar and intergalactic media, and the nature of their sources. Determining the mass composition of HECRs is challenging due to the indirect nature of their detection through air showers and the large fluctuations from shower to shower [7]. The largest source of uncertainty in the shower development comes from the hadronic interactions [6] which cannot be calculated from first principles (non-perturbative Quantum Chromodynamic (QCD)) and require very high computing resources which became available only in the 1990s. The development of hadronic models used in current air shower simulation codes like CORSIKA [8] started during this period.

Nowadays, one of the intriguing phenomena observed in air showers is the "muon puzzle" [9, 10]. Modern air shower detectors such as the Pierre Auger Observatory [11] are based on at least two detection technologies, such as the measurement of the energy deposited along the shower axis by electromagnetic particles (so-called fluorescence detector (FD)) and the measurement of the particle at ground (so-called surface detector (SD)). Current hadronic interaction models struggle to accurately predict the correlation between these two kinds of observables. The measured signal at ground being sensitive to the number of muons produced in air showers, particularly at ultra-high energies and for inclined showers [12]. This discrepancy suggests that our understanding of hadronic interactions at these energy scales is incomplete, and it has sparked interest in exploring new physics mechanisms, including the potential formation of a quark-gluon plasma (QGP) in the early stages of air shower development [13–17].

The potential formation of QGP (or nuclear collective effects in a more general way) in air showers could significantly impact our understanding of hadronic interactions and the properties of HECRs. The study of the effect of a QGP formation in this context offers a unique opportunity to probe the behavior of strongly interacting matter under extreme conditions and to test the predictions of QCD at energy scales beyond those accessible in accelerator experiments. If a model reproducing accelerator data was also able to simulate air showers compatible with cosmic ray measurements, it would mean that we are able to properly extrapolate the physics to higher energy regime.

This paper aims to explore the link between atmospheric air showers and measurements of hadron interactions in accelerator laboratories, and in particular how collective effects in hadronic collisions affects air showers. We will discuss how the newest data from the Large Hadron Collider (LHC) quantifying these effects actually improved significantly the description of air showers.

2. High-Energy Cosmic Rays and Air Showers

When a primary cosmic ray enters the atmosphere of the Earth, it will quickly interact with the nuclei of one of the atoms composing the air (mostly Nitrogen or Oxygen). The energy of the primary interaction can be as high as few 100 TeV in the center-of-mass energy (few 10^{20} eV total energy on a fixed target). It creates hundreds of secondary pions, kaons, and nucleons which propagate further and re-interact until all the energy carried by hadrons is transferred to muons during particle decay or electromagnetic particles via the decay of π^0. The development of air showers can be simulated using models like CORSIKA, which incorporate different hadronic interaction models like EPOS LHC [18], QGSJETII-04 [19, 20], or SIBYLL 2.3d [21]. The study of air showers is essential to understand the composition and energy spectrum of HECRs. Ground-based hybrid detectors, such as the Pierre Auger Observatory, measure the number of particles reaching ground (both of electromagnetic type, like photons and electrons, and muons) and the energy released by air showers in the atmosphere (by fluorescence light or radio antennas) to infer the properties of the primary cosmic rays.

The properties of hadronic interactions, such as elasticity, multiplicity, cross-section, and particle ratios, play a crucial role in determining the characteristics of air showers [22]. The Heitler model [23] provides a framework for understanding the development of electromagnetic cascades, but similar principles can be applied to hadronic showers like in the Matthews-Heitler model [24]:

- **Elasticity**: Elasticity refers to the fraction of energy retained by the leading particle after an interaction. In hadronic interactions, a higher elasticity means that the leading particle carries a larger fraction of the initial energy, leading to a deeper penetration of the shower into the atmosphere. This results in a longer shower development and a higher altitude for the shower maximum.

- **Multiplicity**: Multiplicity refers to the number of secondary particles produced in a hadronic interaction. A higher multiplicity leads to a more rapid development of the shower, as more particles are produced in each interaction. This results in a shorter shower development and a lower altitude for the shower maximum. Additionally, a higher multiplicity can lead to an increased number of muons produced in the shower, as more secondary particles can decay into muons.

- **Cross-Section**: The cross-section quantifies the probability of interaction between the primary cosmic ray and the atmospheric nuclei. A larger cross-section leads to more frequent interactions, resulting in a more rapid development of the shower and a lower altitude for the shower maximum. Conversely, a smaller cross-section implies less frequent interactions and a deeper penetration of the shower into the atmosphere.

- **Particle ratios**: The dominant mechanism for the production of low energy muons (below 100 GeV) 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). However, the energy carried by neutral pions 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 the following interactions and decays. As a consequence, muon production is extremely sensitive to the ratio between π^0 $(+\eta)$ and all other types of particles in each hadronic interaction. High energy muon production are in addition sensitive to the prompt emission due to the decay of heavy-flavored particles (with charm or beauty). Ground based experiment cannot measure these rare particles but in underground (or underwater) large scale neutrino experiments like IceCube [25] or KM3NeT [26], these high energy muons are an important background for the detection of astrophysical neutrinos.

The shower maximum ($X_{\rm max}$) is a critical parameter in the development of air showers, as it provides information about the mass composition of the primary cosmic ray. The depth of $X_{\rm max}$ is influenced by the elasticity, multiplicity, and cross-section of the first few hadronic interactions. A deeper $X_{\rm max}$ indicates a lighter primary particle, as heavier nuclei produce showers that develop higher in the atmosphere due to their larger cross-section and higher multiplicity, as shown on Fig. 1. The lines are simulations with CORSIKA with the latest generation of hadronic interaction models (EPOS LHC-R [27], QGSJETIII-01 [28] and SIBYLL 2.3e [21]). The full lines correspond to a proton primary and the dashed lines to iron primary with a small value of $X_{\rm max}$. Various measurements are represented by points, the most recent and reliable one being from the Pierre Auger Observatory [29, 30] with a transition from light to heavy composition at the highest energies. The exact composition depends on the hadronic model used to interpret the data.

The muon content of air showers is another important parameter determining the mass of the primary cosmic ray. The number of muons (N_μ) produced in a shower is sensitive to the multiplicity and particle ratios of the hadronic interactions, as well as the energy spectrum of the secondary particles [22, 31, 32].

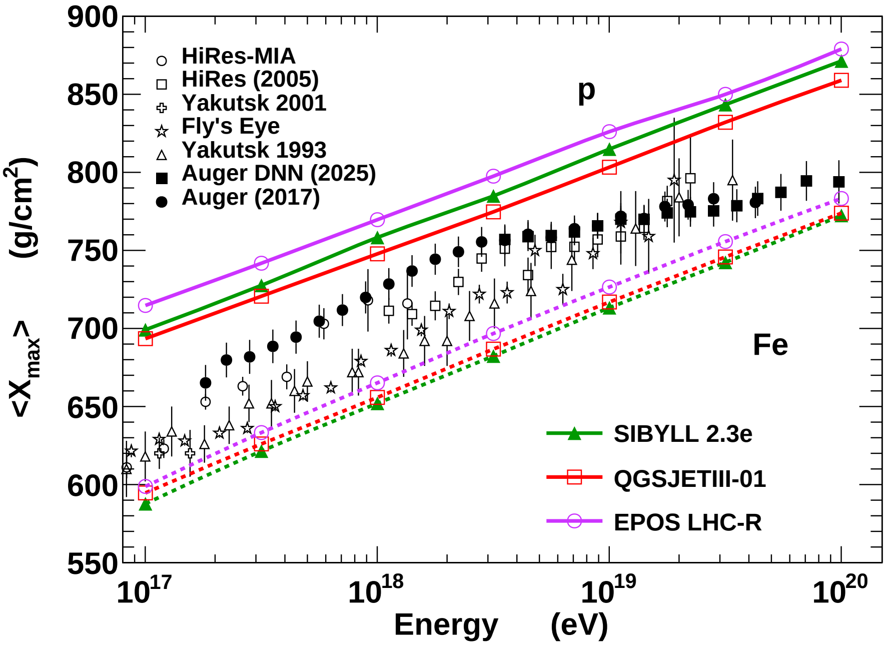

Figure 1: Mean depth of shower maximum $X_{\max}$. Model predictions for different primary particles are compared to data. The Pierre Auger Observatory data are from [29, 30] and the others can be found in [6].

Hybrid cosmic-ray detectors can measure both observables $X_{\max}$ and N$_\mu$ at the same time. Since they are both sensitive to the mass composition, inconsistent measurements (resulting in different compositions) are necessarily related to a deficit in the description of the hadronic interactions. This inconsistency in the description of the data is the so-called "muon puzzle" as observed by the Pierre Auger Observatory [12]. None of the current hadronic models used nowadays is able to reproduce these hybrid data consistently, while a reasonable description of accelerator data up to the LHC is achieved. Despite the fact that it is called a "muon puzzle", most recent studies show that the position of $X_{\max}$ might also be incorrectly predicted by models [33].

As a matter of fact, despite a constant effort to update the models with the latest accelerator data, we can see in Fig. 2 that the differences between EPOS LHC-R (purple dotted line), QGSJETIII-01 (red dashed line) and SIBYLL 2.3e (green dash-dotted line) still remain significant on the basic variables described earlier for proton and pion interaction with air atoms. In particular the evolution of the elasticity as a function of the center-of-mass energy ($\sqrt{(s)}$), is different both in shape and amplitude because it can't be measured directly in collider experiments (lack of forward detector) and depend on model assumptions not well constrained by theory. Some results have been obtained by the LHCf experiment [34] actually leading to a relatively large increase of the elasticity for the EPOS model for instance (the full blue line represents the previous EPOS LHC) and consequently a deeper $X_{\max}$.

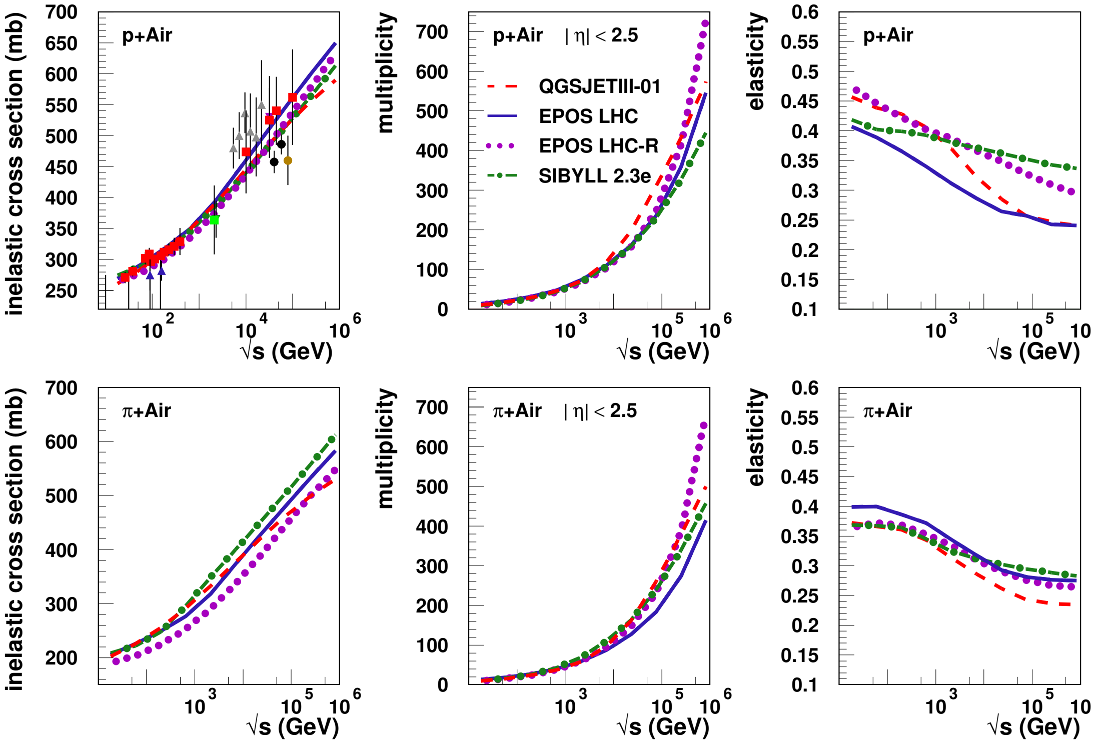

Figure 2: Inelastic cross-section (left-hand side), multiplicity (middle) and elasticity (energy fraction of the leading particle) (right-hand side) for p-air (top) and π-air (bottom) interactions as a function of center of mass energy. Simulations are done with EPOS LHC-R (dotted line), EPOS LHC (full line), QGSJETIII-01 (dashed line), and SIBYLL 2.3e (dash-dotted line). Points are data from [35].

3. Potential Direct Observation of QGP in Cosmic Ray Showers

The possibility of observing the QGP in cosmic-ray showers has been discussed since early times [36]. Some authors were speculating that interactions of ultra-high-energy cosmic rays with air nuclei could lead to a fully thermalized system with a large fraction of strange particles and a reduced production of neutral pions leading to a much larger muon production [37–40]. Different authors predict that a different ratio between high and low energy muons at ground could be observed [41]

However, realistic simulations have shown that a potential direct signature of a QGP in air shower data is experimentally extremely challenging [42]. Furthermore, the study of the fluctuations in the number of muons observed by the Pierre Auger Observatory [43] does not indicate a dramatic change in hadronic interactions even at the highest energies. The number of muons appears to be higher by about 20 to 60% in the data compared to the simulation (depending on the model), but the relative fluctuations are very similar to the predictions of the current model. Since fluctuations are mainly due to the first interaction [31], these data show that first interactions are not special in terms of particle production. The energy spectra of the neutral pions include events with a small fraction of the energy going to π^0 that lead to air showers with a higher muon content AND events with a large fraction of the energy going to π^0 that lead to air showers with a reduced muon content. In order to significantly increase the total number of muons observed at ground level, in a QGP based model applied to the first interaction only, the neutral pion production is always reduced dramatically [37–40], leaving no room for events with a larger energy fraction going to the electromagnetic channel and producing less muons. As a consequence, for this kind of models, the fluctuations in the number of muons are significantly decreased, being in contradiction with the above measurement by the Pierre Auger Observatory.

The QGP might be at the origin of particular events observed in emulsion chambers [44], so-called Centauro events, but the studies were done before the development of modern numerical tools and since there was no satisfactory answer, the topic was abandoned. New analysis would be interesting, taking into account more recent measurements and models.

The ALICE Collaboration's observations of enhanced yields of strange and multi-strange hadrons in high-multiplicity events [45] suggest the formation of QGP in small colliding systems, which could be relevant for UHECR interactions. In that case, it is not the first interaction only that would be largely different, but each of the interactions could transfer a bit less energy to the electromagnetic shower. Thus, we finally have more muons at ground. In [13], it is shown using a semi-analytical calculation, that if the usual particle ratios are replaced by a realistic fraction of particle ratios as produced by a QGP, it could lead to such an effect. The main limitation being that the new ratios were applied to all particles including the one with large longitudinal momentum. The latter can unfortunately not be measured at the LHC because of the lack of detector in this phase space (momentum fraction between 0.001 and 0.1) particularly important for the air shower development. Thus, a large uncertainty on the true effect of the presence of a QGP in the hadronic interactions remains.

4. Collective Effects in Hadronic Interactions

Although it is difficult to find a direct effect of QGP in air shower data, LHC data clearly indicate the presence of at least some collective effects even in proton-proton interactions [45]. The effects seem to be quite universal and do not depend on the system size or energy but on the final multiplicity of the interaction which is a good proxy of the amount of energy which was released by the particle collision. The first model used for EAS simulation that takes into account this effect is the EPOS model [18] using the core-corona approach [46].

4.1 The Core-Corona Approach

The core-corona approach is a theoretical model used to describe the dynamics of heavy-ion collisions and the formation of QGP [46]. It is a very general concept that is not specific to a particular event generator, but it has been developed for the first time in the framework of the EPOS event generator [47], which is also, for the moment, the only model which can be used to study both heavy ion collisions and air shower development. This approach divides the interaction region into two distinct zones: the core and the corona.

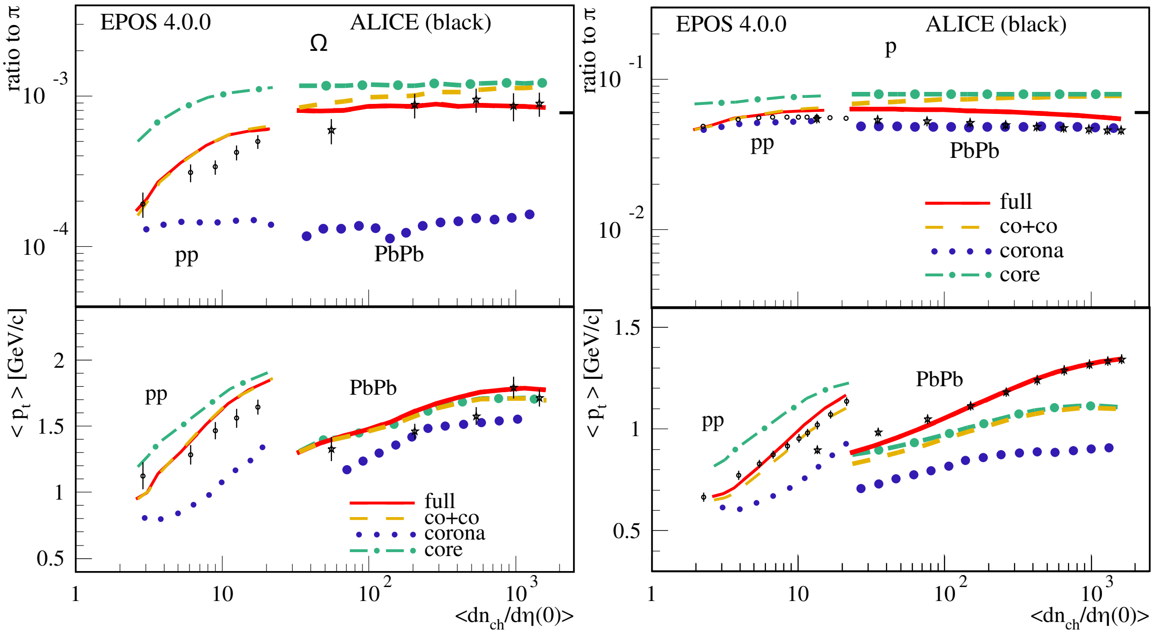

Figure 3: The prediction of the EPOS4 [48] model is shown for the different components and the ALICE data [45] for the Ω/π ratio (upper-left panel) and the p/π ratio (upper-right panel) and $\langle p_t \rangle$ of Ω (lower-left panel) and proton (lower-right panel) as a function of the multiplicity at mid-rapidity. The orange line (co+co) shows the transition from the corona component (blue) to the core component (green). The full model (red line) includes the re-interaction of the produced hadrons (hadronic scattering).

- **Core Region**: In the core region, the energy density is sufficiently high to form a QGP. This region is characterized by the deconfinement of quarks and gluons, which interact strongly and exhibit collective behavior. In central heavy-ion collisions, the core is responsible for a large fraction of the particle production, which will have specific particle ratios (like a large fraction of strange particles typical of a thermal hadronization) and undergo the development of hydrodynamic flow. This is mostly visible at mid-rapidity where the measurements are done.
- **Corona Region**: In the corona region, the energy density is lower and the system remains in a hadronic phase. Particles in this region undergo fewer interactions and can escape the interaction zone more quickly. The corona contributes to the production of high-momentum particles and jets, and in the forward region, that is important for air showers. The particle ratios are typical of the so-called "string fragmentation" as observed in very light systems like the hadrons produced from electron-positron collisions. The string picture is typically used in all event generators that are not based on a thermal model and produce particles along the longitudinal axis.

The core-corona approach allowed significant progress in the description of experimental data in comparison to pure microscopic models ("string" based only) or to pure hydrodynamical models (thermal only) [48]:

1. It provides a more realistic description of heavy-ion collisions by accounting for the in-

homogeneous energy density distribution in the interaction region. This allows for a better understanding of the transition between the hadronic and partonic phases and the centrality dependence.

2. The model can explain various experimental observables, such as the centrality dependence of the suppression of high-momentum particles (jet quenching) or of the collective flow of low-momentum particles. These phenomena are crucial for understanding the properties of QGP.

3. The core-corona approach bridges the gap between microscopic descriptions of particle interactions and macroscopic hydrodynamic models of QGP evolution. This makes it a valuable tool for studying the dynamics of heavy-ion collisions and the formation of QGP.

In particular, it gives a "natural" description of the ALICE data based on particle multiplicity. In Fig. 3, the prediction of the model is shown for the different components and the data on the left-hand side for the Ω particle (multi-strange baryon) and for protons on the right-hand side. In the upper panel, we can see how the Ω/π or p/π ratio changes with the multiplicity at mid-rapidity. The orange line (co+co) shows the transition from the ratio for the corona component (string fragmentation in blue) to the core component (statistical decay in green) because of the increase of the core fraction (QGP) from low-multiplicity p-p events to central Pb-Pb collisions. But in addition to this effect, the full model (red line) includes the re-interaction of the produced hadrons (hadronic scattering (hs) done with URQMD 3.4 [49, 50]) which reduces the particle ratio at the highest multiplicities. The lower panel shows that following the same approach, $\langle \mathrm{p_t} \rangle$ is also described despite the non-continuous evolution from a light to heavy system. In particular we can see that the hadronic scattering is very important for the description of the protons whose ratio looks finally almost like the initial corona alone but with a much larger $\langle \mathrm{p_t} \rangle$.

The particular technical realization of this approach done in EPOS is based on the fact that in this model, all partons (with high or low transverse momentum) are produced in numerous parallel strings (at the same initial time of the collision) taking into account quantum mechanical interferences using the Gribov-Regge picture [51]. The microscopic details of how a core could form and thermalize are not considered, but the assumption is made that if the particle density is large enough in a given region of the phase-space, then the pseudo-particles produced by the strings which are at the origin of this high particle density will either be completely absorbed, and form the core itself if their transverse momentum is too low to escape, or only lose part of their energy if their transverse momentum is high enough. In the latter case, they will be part of the corona. If a pseudo-particle is in a low density region, it simply becomes a particle of the corona component. Most of the strings are produced at mid-rapidity producing a high particle density and then a core in this region. Few of them may extend to much larger longitudinal momentum, producing only few particles in large rapidity region which then be part of the corona. This dynamical picture is not the only way to define the core and the corona [52], but appears to be very successful in describing the accelerator data [53].

Since the core component hadronizes in more baryons and more strange particles, the ratio of π^0 to all other particles is thus lower, and this can have an impact on muon production in air showers [13]. This approach is then very important to be taken into account in air shower simulations.

4.2 Tuning the Models for Air Shower Simulations

The hadronic interaction models used in CORSIKA to simulate EAS are based on basic theoretical principles, but there is a large part of phenomenology with parameters that are tuned to experimental measurements, in particular in the string fragmentation used by all the models to produce hadrons. The measurements are mostly at mid-rapidity but the EAS development is sensitive to particles carrying a large fraction of the energy which are then emitted at large rapidities. The role of the model is then to extrapolate from observed data at mid-rapidity to large rapidities and to higher energies.

The link between low and high energy depends on the model itself, but was though to be relatively well constrained by the theory. Since hadronic interactions with air's atom as target was considered as a "light" system, there were done NOT taking into account any collective effect. ALICE data show that at multiplicities easily reached by collisions of hadrons or nuclei with air [13], some collective effects are observed and should be taken into account. This was actually the missing piece of the "puzzle". Indeed, for a given visible multiplicity, if there is collective effects, heavier particles are produced (more baryons and more strangeness) with larger transverse momentum because of the flow, thus the total energy per produced particle is larger in average. This implies that more energy is taken out of the projectile and a lower elasticity is observed. This means that if the collective effects are taken into account, the simulated $X_{\rm max}$ will be reduced, for example. For instance in the EPOS framework, for the core-corona approach to reproduce the data, it is necessary to have more multiple scattering (more jets) between the constituent partons of the beam particles (different parameters and cross-section) and this reduces the energy of the beam remnant (elasticity of the leading particle). These collective effects increase with energy and the mass of the colliding system, changing the extrapolation from low to high energy and from low to higher mass.

Furthermore, the models used for air shower simulations were tuned based solely on hadronic interactions in order to maintain a small number of parameters and a simple approach for improved predictive power. However, a global approach that considers all possible collective effects makes it possible to use hadronization data from electron-positron annihilation experiments. Even in these simple systems, the local density of produced particles could be high enough to observe hadronic rescattering, which modifies the particle ratios. This also provides access to more data on exotic particles, such as high-mass resonances like the $\eta\prime$ and f_0, which can modify the neutral-to-charged π or ρ ratios by their decay. Consequently, the free parameters of string fragmentation must be modified to properly describe these data, resulting in different particle ratios than when hadronization is tuned to hadron data only.

The particle ratios at mid-rapidity are also changed by the hadronic scattering (with or without a QGP). Since these collective effect occurs only where the particle density is large, it will not affect the large rapidities. Thus, the correlation between forward and mid-rapidity particle production is modified if the presence of the rescattering is taken into account. Again, this will lead to some parameter tuned in a different way and to different predictions at large rapidities: when the collective effects are not taken into account, the models will fix the parameters with some measurement at mid-rapidity and get the same type of hadronization at large rapidity where there are not enough data available to do the tuning. In recent measurements such as NA61 data [54], the models were unable to adequately describe the full phase space for some important particles, meaning that this approach was too limited. Using a model in which the parameters were tuned taking into account the collective effects, a different hadronization is obtained for different phase-spaces and the data are better reproduced. Thus, the lack of knowledge about the collective effects in light colliding system, resolved by the new data from the LHC experiments, could explain to a large extent the origin of the "muon puzzle" [55].

To better illustrated the different effects, various flavors of the same hadronic interaction model (here EPOS) were used to simulate air showers, whose normalized $X_{\max}$ and the total number of muons at ground N_μ are shown in Fig. 4:

- **"pp tune (no coll.)"**, represented by a dashed (blue) line, correspond to a model like SIBYLL 2.3e or QGSJETIII-01 where the string fragmentation is tuned on hadronic interactions only and without collective effects. It is the reference line.
- **"pp tune + cc"**, the dotted (red) line, uses only hadronic data but this time including core-corona (cc) but without hadronic scattering (hs). It allows to test the effect of the core-corona approach alone.
- **"ee tune + hs"**, the dash-dotted (brown) line, uses leptonic data to tune the string fragmentation including hadronic scattering but without core-corona. It allows to test the effect of using a different string fragmentation alone.
- **"ee tune + mult. tune + cc + hs"**, the full (purple) line, includes all the collective effects and the new string fragmentation.

Each flavor is tuned to reproduce accelerator data as accurately as possible, but only the last one can reproduce all LHC data in full detail. Taken individually, both the core-corona and the new string fragmentation with hadronic scattering impact $X_{\max}$ (reduction) and N_μ (increase) similarly. Consequently, using both simultaneously has a cumulative effect, increasing N_μ by up to 20%.

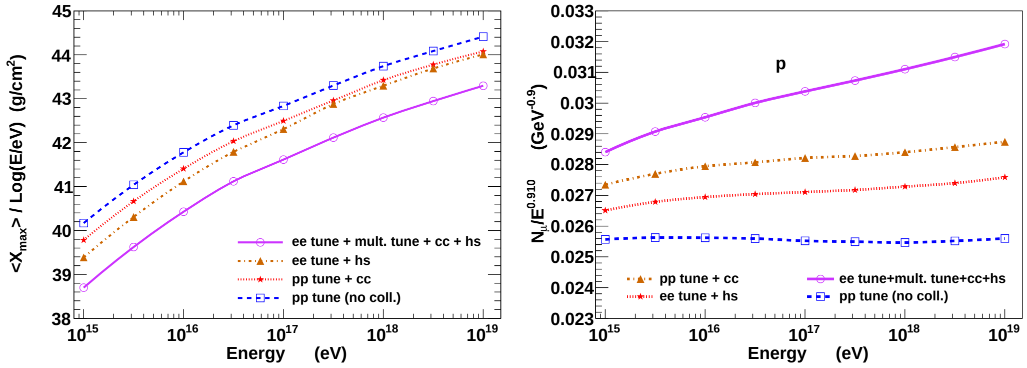

Figure 4: Mean depth of shower maximum $X_{\max}$ normalized by Log(E/eV) (left-hand side) and N_μ normalized by $E^{0.91}$ (right-hand side) for different model predictions (see text).

5. Air Shower Simulations with Collective Effects

Thanks to the knowledge accumulated on the properties of QGP, it has been possible to develop and tune a first model, called EPOS LHC-R [55], taking into account these collective effects to simulate air showers. For the moment, other models used to simulate heavy-ion collisions cannot be used for air showers for technical reasons, but efforts are ongoing [56–58]. The results are shown in Fig. 1 and 5.

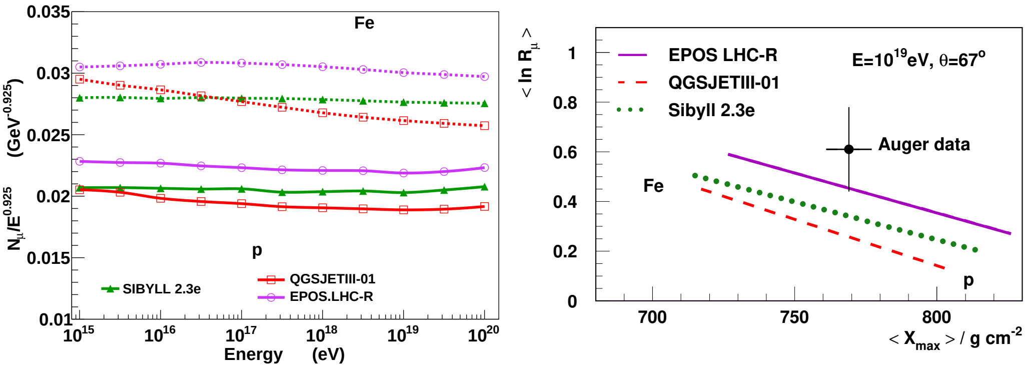

Figure 5: Left-hand side: N_μ normalized by $E^{0.925}$ full lines are for proton induced showers and dashed lines for iron induced showers. Right-hand side: $X_{\max}$ and $\langle \ln R_\mu \rangle$ as measured by the Pierre Auger Observatory [12] (point). The purple lines are predictions using EPOS LHC-R, the dashed lines are for QGSJETIII-01 and the dashed-dotted line for SIBYLL 2.3e.

The total number of muons N_μ and the link between $X_{\max}$ and $\langle \ln R_\mu \rangle$ as measured by the Pierre Auger Observatory [12] (point) is shown with the predictions using EPOS LHC-R (purple lines), QGSJETIII-01 (red lines), and SIBYLL 2.3e (green lines). $\langle \ln R_\mu \rangle$ is the logarithm of the relative number of muons compared to the QGSJETII-03 model ($\langle R_\mu \rangle = 0$ corresponds to proton-induced showers generated with the QGSJETII-03 model). Currently, only EPOS LHC-R is tuned using a global approach, which leads to a higher value of N_μ and $\langle R_\mu \rangle$. Combined with the deepest $X_{\max}$, it makes it compatible with the experimental point. The new QGSJETIII-01 does not include collective effects and remains in the region covered by all other models used for air shower simulations, such as SIBYLL 2.3e, and remains incompatible with the Auger data point despite being tuned using the same accelerator data as EPOS LHC-R. Nevertheless, both QGSJETIII-01 and EPOS LHC-R have a higher value of $X_{\max}$ compared to the previous version QGSJETII-04 and EPOS LHC after being retuned to the latest LHC data.

Previous studies showed that the "muon puzzle" could be solved using some properties of QGP formation (such as strangeness enhancement), but it was done using simple theoretical models or artificial modifications of existing hadronic models [13, 15, 16, 59], leaving space for large uncertainties. Now using a true event generator based on a coherent and global approach for heavy-ion collisions, it confirms that it is possible to be compatible with both the LHC and the Pierre Auger Observatory data. More studies will be needed to check if there are other ways to reach the same results or if taking the QGP formation is the only key to solving the puzzle.

As a consequence, thanks to the LHC data and using a global approach taking into account collective effects, it is now possible to interpret cosmic-ray data consistently using $X_{\max}$ or N_μ. From Fig. 1 it is clear that the average mass composition extracted using the EPOS LHC-R model, for instance, will be larger than with the other models. In particular, it can be seen that, at the highest energy, the data points reach the iron line. This is extremely important in understanding the origin of the ultra-high-energy cosmic rays.

6. Conclusion

The study of cosmic rays and their interactions with the Earth's atmosphere reveals a complex interplay between high-energy particle physics and astrophysics. Cosmic rays, ranging from medium to ultra-high energies, produce extensive air showers upon interacting with atmospheric nuclei. These showers provide valuable information about the primary particles, including their mass composition and energy spectrum.

The analysis of air showers has highlighted challenges, notably the "muon puzzle," where current hadronic interaction models fail to accurately predict muon production for a given primary mass. This discrepancy suggests an incomplete understanding of hadronic interactions at ultra-high energies and has sparked interest in exploring new physic mechanisms, including the potential formation of a quark-gluon plasma (QGP) in air showers.

The core-corona approach divides the interaction region into a high-energy-density core and a lower-energy-density corona. It has been developed to provide a more realistic description of heavy-ion collisions and QGP formation. This approach significantly improves the description of experimental data. This recent progress in understanding hadronic interactions allows us to fully account for the collective effects due to QGP formation. A global approach that uses experimental data from electron-positron annihilations to heavy-ion collisions, together with this new theoretical progress, shows improved agreement with EAS observations, particularly regarding the relationship between the shower maximum, $X_{\max}$, and the muon content, as observed by the Pierre Auger Observatory.

In summary, the study of cosmic rays and air showers, taking into account the role of collective effects, offers a unique opportunity to probe the behavior of strongly interacting matter under extreme conditions. Uncertainties remain, in particular in pion interactions, but this interdisciplinary approach enhances our understanding of cosmic ray physics and contributes to the broader field of particle physics.

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