The Muon Puzzle in Cosmic Ray Induced Air Showers and possible solutions

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Abstract

High-energy cosmic rays are messengers of extreme astrophysical events and therefore offer an unique view into the universe. High-energy cosmic rays induce particle cascades, called air showers, in Earth's atmosphere, which are also the main sources of diffuse background for neutrino and gamma ray observatories. Air showers are the only feasible way to observe high-energy cosmic rays. Inference of cosmic ray properties requires a quantitatively correct physical model of the hadronic interactions in an air shower. Current models are challenged by the Muon Puzzle: a growing discrepancy in the description of muons produced in air showers over shower energies from a few PeV to tens of EeV, which was confirmed in 2018 at 8σ by a collaboration of eight air shower experiments. The Muon Puzzle points to a common mismodeling of hadron production in soft hadron-ion collisions and thus presents a unique opportunity to learn more about non-perturbative QCD in hadron–nucleus collisions. To address it, several experiments at the LHC study forward hadron-production in proton-ion collisions. Very important in the next years will be the planned measurements with oxygen beams in the LHC to study proton-oxygen collisions at the highest energies.

1 Introduction

Cosmic rays are highly energetic nuclei from astrophysical sources. They are charged and bent onto chaotic paths by extrasolar magnetic fields and appear isotropic in the sky. The arrival directions cannot be used to learn about their origins, but the energy spectrum and the elemental composition carry an imprint of the sources.

Cosmic rays with energies larger than 10^{15} eV can only be indirectly observed via extensive air showers. By measuring the energy deposit of the air shower, the longitudinal depth X_{max} of its maximum in the atmosphere and the muon abundance N_μ, one can infer the energy and mass (which is identifying the element) of the cosmic ray. A detailed understanding of the hadronic physics in an air shower is needed to accurately infer energy and mass from air shower observables. The actual observables can be well measured with an accuracy of 10 % of the proton–iron difference by leading experiments [1], but the inferred mass is ambiguous, because air showers are not consistently described by simulations.

The problem is illustrated by Fig. 1, in which the elemental composition is summarized by the mean-logarithmic mass $\langle \ln A \rangle$ and shown as a function of the cosmic-ray energy E. The predictions for $\langle \ln A \rangle$ (lines) for different origin theories vary strongly. It is technically feasible to measure $\langle \ln A \rangle$ accurately enough in leading experiments to severely constrain origin theories. However, actual measurements form wide envelopes due to variations in the hadronic interaction models used to simulate

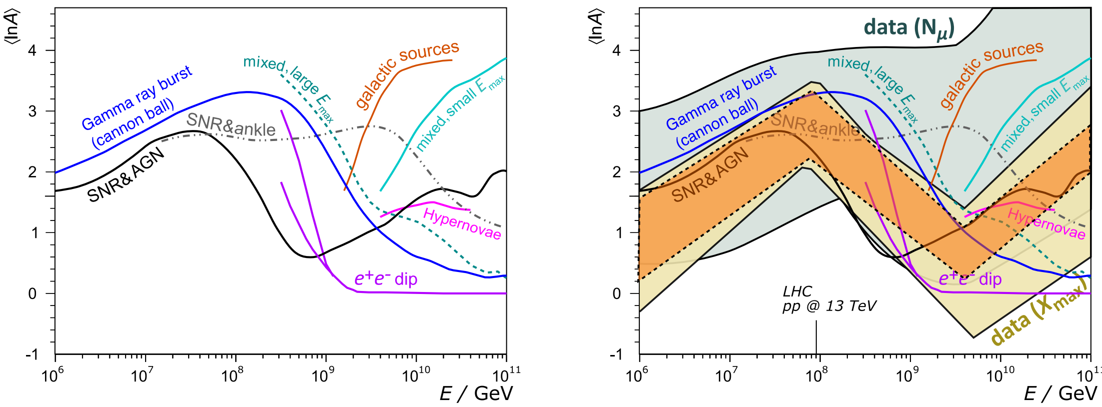

Figure 1: Mass composition of cosmic rays quantified by $\langle \ln A \rangle$ as a function of cosmic-ray energy E. Model predictions (markers and lines) are compared to data bands, all taken from the review by Kampert and Unger [2]. The left plot shows predictions from astrophysical models that assume different dominant sources. The right plot shows an overlay of the spread of experimental data, grouped by the type of air shower variable used ($X_{\max}$ or N_μ, see text for details). The dotted band is a projection of the purely experimental uncertainties in current leading experiments. The arrow at the bottom shows a collisions at the LHC equivalent in center-of-mass energy to the first interaction.

the air shower development (different experiments use different interaction models to convert their measurements to $\langle \ln A \rangle$).

The disagreement between the mass composition inferred from N_μ and $X_{\max}$ is the main obstacle. Muon measurements above about 10^{17} eV suggest a heavier mass composition than measurements based on the shower depth [2]. When combined, the measurements cover the whole parameter space and no theory can be excluded. The average composition is not expected to be heavier than iron, but that is suggested by several muon measurements [3–5]. This discrepancy between air shower simulations and measurements is called the Muon Puzzle.

Muons are produced after several generations of hadronic interactions in air when light mesons decay rather than interact again with air nuclei. The number of muons produced in this way is a function of several characteristics of microscopic hadronic interactions in air showers [6,7]. Influential are the number of light hadrons produced and the fraction of energy diverted into neutral pions for particles produced in the forward region. More data on the production of light hadrons in the forward direction is needed from collider experiments [8] and studies are ongoing, in particular in LHCb. The common disagreement of all hadronic interaction models – which are tuned to collider data on centrally produced hadrons – with air shower data suggests that something fundamental is off in our understanding of light hadron production in the forward direction, which is governed by soft-QCD.

2 Experimental data on the Muon Puzzle in air showers

In 2018, a working group was formed by members of eight leading air shower experiments for the UHECR 2018 workshop in Paris, France, with the goal to review and combine the existing muon measurements [3, 5, 9–17]. The joint report [4] was signed by the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, Yakutsk EAS Array collaborations, which is a great achievement and unprecedented in this field.

The report establishes the Muon Puzzle as an experimental fact: the muon abundance increases faster with the shower energy than all current predictions. The abstract z scale was introduced to

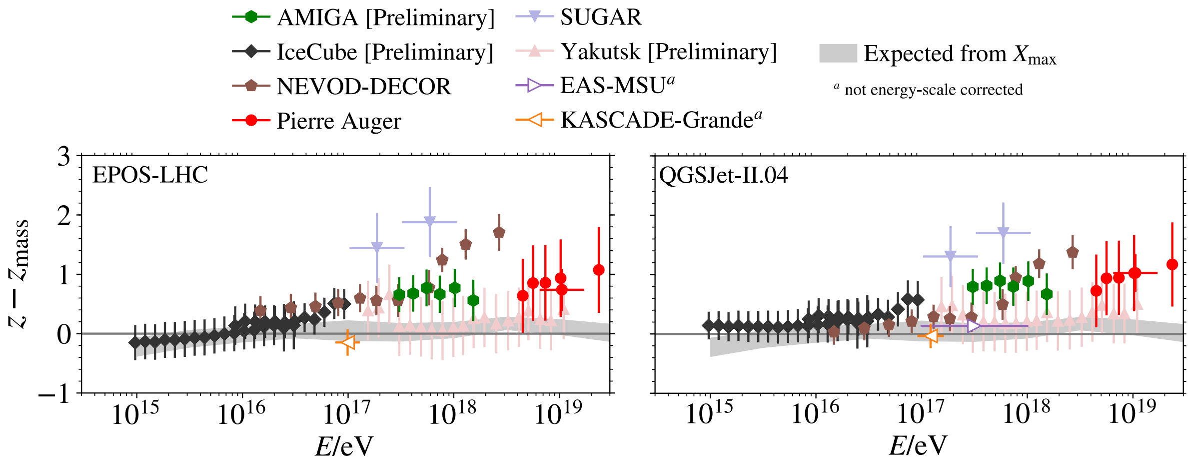

Figure 2: Difference between observed z and the expectation from X_{max} measurements from Ref. [4]. The positive slope of the combined data is highly significant to 8σ, since the error bars mostly show positively correlated systematic uncertainties.

demonstrate this,

$$z = \frac{\ln N_\mu - \ln N_{\mu_p}^{\text{sim}}}{\ln N_{\mu_{\text{Fe}}}^{\text{sim}} - \ln N_{\mu_p}^{\text{sim}}}, \tag{1}$$

where $\ln N_\mu$ is the logarithm of the measured muon abundance estimate and $\ln N_{\mu_p}^{\text{sim}}$ and $\ln N_{\mu_{\text{Fe}}}^{\text{sim}}$ are simulations of the estimate for proton and iron showers. The measured shower energy enters implicitly in $\ln N_{\mu_p}^{\text{sim}}$ and $\ln N_{\mu_{\text{Fe}}}^{\text{sim}}$. These numbers are usually obtained by simulating air showers at the measured energy E that corresponds to the measured N_μ.

The z scale has several advantages. The strong energy dependence of N_μ is absorbed and very diverse muon number estimators are converted into a comparable number. The z-values are sensitive to the energy-scale, so a cross-calibration of the experimental energy scales was performed, which significantly reduced the systematic scatter between experiments. Since the z scale depends on the simulation, values for six hadronic interaction models were studied; three leading post-LHC models [18–20], and three older pre-LHC models [21–23]. No model predicted the increase that is observed in data. The discrepancy is shown for the two most common models in Fig. 2. Only by combining all datasets, a faster-than-predicted increase of the muon abundance with energy could be established at 8σ. Using measurements over five orders of magnitude in energy provides the necessary lever-arm, and the cross-calibration reduced the overall uncertainty of the combined data.

Establishing the Muon Puzzle at a high significance was very important to raise awareness in the collider community about this issue. The report was pivotal in a proposal to accelerate oxygen ions at the LHC [8] and to collide them with protons at a center-of-mass energy of 10 TeV, which would mimic the first interaction of a 10^{17} eV cosmic-ray proton with air. Accelerating oxygen beams at the LHC is currently planned for 2023.

3 Hadron production in hadron-ion collisions at the LHC

The formation of the air shower cascade is a complex process. This makes connecting the observed muon discrepancy with observables in collider experiments a challenge. Muons are produced at the end of a hadronic cascade and yet the issue must be in the first interactions, since showers at lower energies (which are effectively later stages of showers at higher energy) seem to be adequately described.

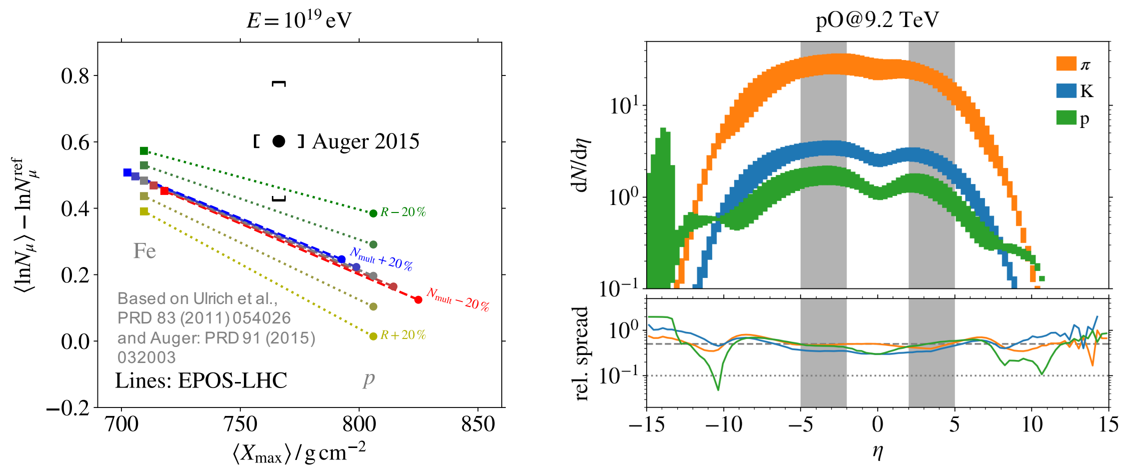

Figure 3: Left: Lines show predictions from the hadronic interaction model EPOS-LHC for the averages of X_{max} and $\ln N_\mu$ for 10^{19} eV air showers, from Ref. [8]. In this log-log plot, any possible elemental composition (from pure proton to pure iron) produces a point on a line. The data point with brackets indicates a representative measurement by the Pierre Auger Observatory with systematic uncertainties. Changing hadron multiplicity N_{mult} moves the model line parallel to itself. Only by reducing R can the line be moved upwards to meet the data point. Right: Model spread of EPOS-LHC, QGSJet-II.04, and SIBYLL-2.3 for charged pion, kaon, and proton production in a proton-oxygen collision at 9.2 TeV. Grey bars show the LHCb acceptance. The model spread is about 50 % in the forward region, even though it is only 5 % at mid-rapitity in proton-proton collisions at 13 TeV.

The simplified Heitler-Matthews model [6] has proven itself as a viable tool to study these connections. It points to the hadronic energy flow as the most important factor for the muon abundance. At each step of the cascade, some energy is diverted into an electromagnetic subshower by decays of neutral pions, which are copiously produced in hadronic interactions. Feedback from the electromagnetic subshower into muons is negligible, therefore the diverted energy is lost for muon production. This places prime importance on measuring the energy ratio

$$R = \frac{\text{energy carried by neutral pions}}{\text{energy carried by other hadrons}}, \tag{2}$$

an experimental proxy for the energy fraction carried away by neutral pions in hadron-ion collisions. These insights were quantitively confirmed by full air shower simulations with ad hoc modified hadronic interactions [7, 8]. The impact of R on muon production in air showers and current uncertainties in forward hadron production are illustrated in Fig. 3.

Since energy flow in hadron-ion collisions is important, the experimental focus is put on forward hadron production. While most particles are produced at mid-rapidity, the largest energy per particle is carried by the most forward produced particles. Between these two extremes is the important rapidity region, illustrated in Fig. 4 for proton-proton and proton-lead collisions at the LHC. The excellent data available at mid-rapidity on hadron production from ALICE in proton-proton and proton-lead collisions [24] alone is not able to resolve the Muon Puzzle for two reasons. Firstly, particles produced at mid-rapidity only produce a negligible amount of muons in a full air shower cascade. The data is very important for model tuning, but does not cast direct light on the Muon Puzzle. Secondly, the nuclear modification of production cross-sections in proton-ion collisions is very strong for forward-produced particles and not accurately predicted by theory. The modification factor R_{pPb} = cross-section in p-Pb collions/(cross-section in p-p $\times$ 208) is far away from 1 for J/ψ production measured with LHCb [25] and in neutral pion production measured with LHCf [26]. The

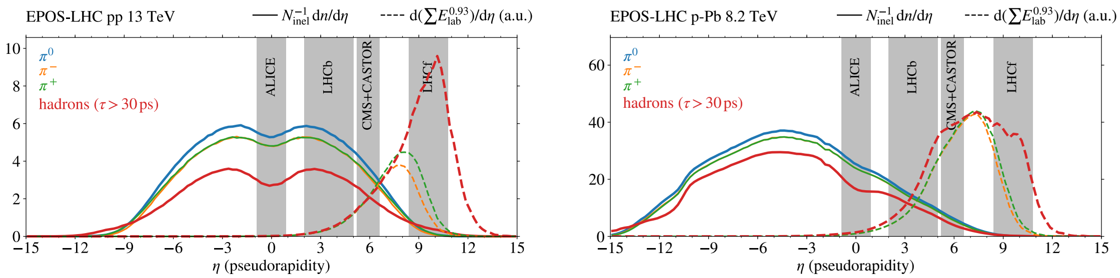

Figure 4: Shown are the spectra of pions and long-lived hadrons produced in proton-proton collisions at 13 TeV (left-hand side) and proton-lead collisions at 8.2 TeV (right-hand side) in solid lines. These spectra were converted into estimates of the number of muons that would be produced by these hadrons in air showers (dashed lines, not to scale). The most relevant phase-space to resolve the Muon Puzzle is the one where the produced number of muons is large. Grey bands show the acceptance of several LHC experiments for comparison.

importance of nuclear effects has been further emphasized by a recent measurement [27] of R in proton-proton collisions at 13 TeV by the CASTOR experiment, which showed that current hadronic interaction models predict a value that is already too low, while it must be even lower than the current values in hadron-nitrogen and hadron-oxygen collisions to solve the Muon Puzzle.

For solving the Muon Puzzle, specialized forward detectors like CASTOR [28] and LHCf [29] are very important, since these cover the most relevant phase-space. Equally important are complementary measurements with LHCb [30]. LHCb is a general purpose forward spectrometer with particle identification capabilities in the region $2 < \eta < 5$, which is unique among the four large LHC experiments. It can study charged pions, kaons, and protons in the forward direction in great detail at the onset of the relevant phase-space for air showers, while the specialized forward detectors are limited to energy flow in case of CASTOR and neutral particles in case of LHCf. Several measurements in LHCb to that end in proton-proton and proton-lead collisions at the highest LHC energies are currently underway.

Very important will be follow up measurements of these interactions in proton-oxygen beam collisions, which were proposed in Ref. [8] and are planned for 2023, near the end of Run 3 of the LHC. Together with proton-proton and proton-lead measurements, these measurements will allow us to study the evolution of forward production with the size of the nucleus purely in data. These measurements will severly constrain R in proton-oxygen collisions, achieving an accuracy of 5 % seems realistic. According to our quantitative projections, these measurements should resolve the Muon Puzzle in air showers and thus to shed light on the missing physics in the soft sector of QCD.

4 Conclusions

The Muon Puzzle in air showers points towards missing physics in the soft-QCD sector of hadron-ion collisions, since none of the current hadronic interaction models is able to consistently describe air shower and LHC data. Projections show that the origin of the discrepancy must be observable in measurements of forward hadron production at the highest LHC energies. The relevant forward region is covered by specialized forward experiments at the LHC, CASTOR and LHCf, and by the general purpose spectrometer LHCb. Studies of hadron production in proton-proton and proton-lead collisions with LHCb are currently ongoing. Together with future data from high-energy proton-oxygen beam collisions at the LHC, these measurements have the potential to solve the Muon Puzzle.

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