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Probing the energy spectrum of hadrons in proton air interactions at ultrahigh energies through the fluctuations of the muon content of extensive air showers

Lorenzo Cazon [a], Ruben Conceição [a,b], Felix Riehn [a,*]

[a] Laboratório de Instrumentação e Física Experimental de Partículas (LIP) – Lisbon, Av. Prof. Gama Pinto 2, 1649-003 Lisbon, Portugal
[b] Instituto Superior Técnico (IST), Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal

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ABSTRACT

We demonstrate that the shower-to-shower fluctuations of the muon content of extensive air showers correlate with the fluctuations of a variable of the first interaction of Ultra High Energy Cosmic Rays, which is computed from the fraction of energy carried by the hadrons that sustain the hadronic cascade. The influence of subsequent stages of the shower development is found to play a sub-dominant role. As a consequence, the shower-to-shower distribution of the muon content is a direct probe of the hadron energy spectrum of interactions beyond those reachable in human-made accelerators.

1. Introduction

Ultra-High-Energy Cosmic Rays (UHECRs) collide with nuclei of the Earth's atmosphere at center-of-mass energies that surpass the LHC energy scale, creating huge cascades of particles, the Extensive Air Showers (EAS) [1]. EAS constitute an unique experimental opportunity to explore hadronic interactions well beyond the energy scale attained by the largest human-made accelerator, the Large Hadron Collider (LHC).

On the other hand, the precise composition of UHECR is still unknown, as the nature of the primaries has to be inferred from EAS measurements themselves by using phenomenological models of the hadronic interactions tuned to a limited range in energy and kinematic phase-space. Breaking this degeneracy is one of the challenges currently faced by UHECR physics. This is to be achieved by increasing the number of independent observables taken from EAS.

Muons are direct messengers from the hadronic activity within EAS. The overall muon number can signal inconsistencies in the shower description. In fact, measurements at the Pierre Auger Observatory have shown that simulations, using the LHC-tuned hadronic interaction models, underestimate the muon content in air showers [2,3]. It has also been shown that the shower-to-shower variation in the muon content is useful information in discerning the composition of UHECR primary [4]. As a consequence, the effort to better measure EAS muons is increasing and several experiments are deploying upgrades to their detectors to enhance the sensitivity to them (see for instance [5]).

It is thus necessary to deepen research into the phenomenology of the muon component and in particular to understand the shower-to-shower distributions.

In this letter, we demonstrate that the fluctuations of the muon content of EAS directly correlate with the fluctuations of a variable that probes the hadron energy spectrum of the first interaction. The subsequent shower interactions give the overall scale of the muon content, but play a sub-dominant role in the shower-to-shower fluctuations.

2. The shower-to-shower fluctuations in the muon content of proton-induced EAS

EAS initiated by UHECRs develop in two components: the hadronic and the electromagnetic (EM) cascades. The EM component consists of photons, electrons and positrons. It arises from the

* Corresponding author.
E-mail address: friehn@lip.pt (F. Riehn).

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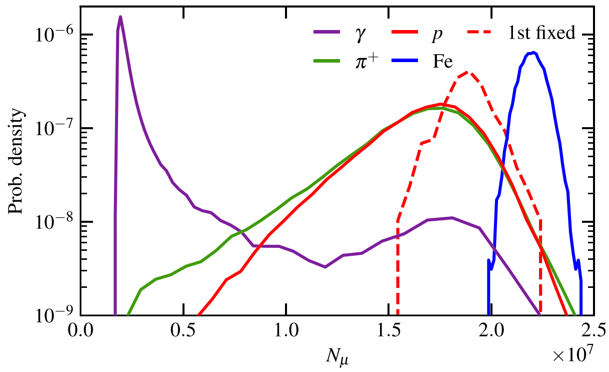

Fig. 1. Distribution of the total number of muons produced in simulated EAS initiated by different primaries. The results for a proton primary, where the multiparticle production of the first interaction is fixed, is shown by the dashed line. Simulations were done with CONEX using EPOS-LHC and FLUKA as high and low energy interaction models respectively.

EM decay of mesons in the hadronic component, predominantly from neutral pions, π^0. Photons and electrons in the EM cascade only rarely undergo interactions that produce hadrons. In each interaction, approximately a third of the energy is transferred from the hadronic to the EM cascade, corresponding to the π^0 production rate. As the energy within the hadronic cascade decreases, it eventually becomes more likely that unstable hadrons decay rather than interact, this being the stage of the hadron cascade where most muons are formed [1,6].

In Fig. 1 the shower-to-shower distributions of the number of muons, N_μ, for ensembles of simulated air showers initiated by different primaries are shown. The primary energy is 10^{19} eV and the zenith angle is 67°. We define N_μ as the number of muons with $E > 1$ GeV arriving at ground. If one considers lower zenith angles the truncation of the muon production distribution and the muon propagation [7] change the resulting distributions, although their main characteristics remain the same (see Appendix A).

At 10^{19} eV, air showers typically contain 10^7 muons with $E > 1$ GeV. In Fig. 1, one sees that the distribution differs substantially between different primaries. The relative fluctuations $\sigma[N_\mu]/\langle N_\mu\rangle$ for proton primaries are ~ 0.15 (post-LHC model average).[1] In general, this value is much larger than $1/\sqrt{\langle N_\mu\rangle} = 10^{-4}$, which is what one would obtain if the muons in the EAS were produced independently. Instead, the relative fluctuations indicate that the number of independent participants is $1/0.15^2 \sim 44$, a value of the same order as the number of particles typically produced in a single hadronic interaction. This suggests that the fluctuations could be dominated by phenomena in the first interaction. This idea has been tested with a modified air shower simulation wherein the first interaction has been fixed and showers were simulated by reinjecting all secondaries from this particular first interaction. The resulting effect on the distribution of the number of muons is shown in Fig. 1 by the dashed line. It can be seen that the width of the distribution is reduced while the average remains the same. The relative fluctuations in this modified simulation are much lower, around 0.05.

A simple yet effective picture to understand this in terms of the shower dynamics is provided by Heitler–Matthews (HM) type models [8]. In such models, air showers are described as codeveloping EM and hadronic cascades, where all hadronic interactions yield a constant multiplicity. The produced particles are separated into two groups, those that decay into EM particles (π^0), feeding the EM cascade, and those that remain in the hadronic cascade ($\pi^\pm$), accounting for the hadronic multiplicity. In each interaction, energy is equally shared by all produced particles. The variable describing the development of the shower is the generation number, i, which counts the number of interactions a particle has undergone. Particles arising from the first interaction are generation $i = 1$. Due to the equipartition of energy and to the transfer to the EM cascade, the energy in the hadronic cascade rapidly decreases. When it falls below a critical energy, E_c, the cascade is terminated and the hadronic particles decay into muons. The average number of muons in the shower can be written as a function of the total ($m_{\rm tot}$) and hadronic (m) multiplicity:

$$\langle N_\mu(E)\rangle = m^g = \mathcal{C}\, E^\beta . \tag{1}$$

Here g is the *critical generation* number, E is the energy of the primary particle, $\mathcal{C} = E_c^{-\beta}$ is a normalization constant, and $\beta = \ln m/\ln m_{\rm tot}$. We have set β to 0.93, taken from post-LHC hadronic interaction models (Appendix B).

In order to understand the shower-to-shower fluctuations of N_μ, one must consider that the multiplicity varies from interaction to interaction. The average hadronic multiplicity in generation i can be calculated as $m_i \equiv N_i/N_{i-1}$, where N_i (N_{i-1}) is the number of interacting hadrons in generation i ($i-1$). The number of muons in the shower is then $N_\mu = \prod_{i=1}^{g} m_i$. Note that, while the critical generation, g, is well defined for the HM model, allowing fluctuations of the hadronic multiplicity changes the overall energy budget of each sub-shower, leading to the fluctuation of the generation where the energy threshold E_c is reached. Therefore, g must now be understood as an average parameter for the whole shower.

Assuming the hadronic multiplicities of all interactions arise from a common probability distribution with mean, m, and dispersion, $\sigma(m)$, the fluctuations of m_i are given by

$$\sigma(m_i) = \frac{\sigma(m)}{\sqrt{N_{i-1}}} . \tag{2}$$

We thus find that the fluctuations of the average multiplicity in generation i are suppressed by the number of interactions resulting from the previous generation N_{i-1}. As the number of particles/interactions grows exponentially with the number of generations, the contributions to the fluctuations from later shower stages become increasingly smaller. This behavior is typical for cascade processes with fixed multiplicity, as they occur in photomultiplier tubes [9,10].

In addition, for realistic multiplicity distributions, $\sigma(m)$ decreases with energy [11]. As the interaction energy decreases from one generation to the next, fluctuations from later stages are further suppressed. We conclude that the overall fluctuations in the number of muons are dominated by the fluctuations in the first interaction, and that the contributions from further generations are exponentially suppressed.

So far, fluctuations of the shower were explained by fluctuations of the particle multiplicity. Nevertheless, an additional source of fluctuations comes from the fact that in each interaction, energy is shared among the emerging particle in a uneven and stochastic way. Taking into account only those fluctuations arising from the first interaction, one can write the total number of muons as the sum of the average number of muons that are produced in the m_1 subshowers that come out of the first interaction, i.e.

$$N_{\mu,1}(E) = \sum_{j=1}^{m_1}\langle N_\mu(E_j)\rangle = \sum_{j=1}^{m_1}\mathcal{C}\, E_j^\beta , \tag{3}$$

[1] The variation across interaction models of the relative fluctuations for proton primaries is 8%. See Appendix B for details.