

Study of muon bundles from extensive air showers with the ALICE detector at CERN LHC

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Abstract. ALICE is one of four large experiments at the CERN Large Hadron Collider, specially designed to study particle production in ultra-relativistic heavy-ion collisions. Located 52 meters underground with 28 meters of overburden rock, it has also been used to detect muons produced by cosmic-ray interactions in the upper atmosphere. The large size and excellent tracking capability of the ALICE Time Projection Chamber are exploited to study the muonic component of extensive air showers. We present the multiplicity distribution of these atmospheric muons and its comparison with Monte Carlo simulations. The latest version of the QGSJET hadronic interaction model was used to simulate the development of the resulting air showers. High multiplicity events containing more than 100 reconstructed muons were also studied. Similar events have been studied in previous underground experiments such as ALEPH and DELPHI at LEP without satisfactory explanations for the frequency of the highest multiplicity events. We demonstrate that the high muon-multiplicity events observed in ALICE stem from primary cosmic rays with energies above 10^{16} eV and that the frequency of these events can be successfully described by assuming a heavy mass composition of primary cosmic rays in this energy range.

1. Introduction

ALICE (A Large Ion Collider Experiment) [1], designed to study the Quark Gluon Plasma (QGP) in ultra-relativistic heavy-ion collisions at the CERN Large Hadron Collider (LHC) has also been used to perform studies that are of relevance to astro-particle physics. ALICE carried out a program of cosmic-ray data taking, during periods with no beams in the accelerator, between 2010 and 2013. A total of 30.8 days of data were taken, resulting in approximately 22.6 millions events with at least one reconstructed muon.

The muons collected in ALICE are created in Extensive Air Showers (EAS) that develop after the interaction of primary cosmic rays with nuclei in the upper atmosphere. In this study we find that primaries with energy $E > 10^{14}$ eV give rise to *multi-muon events* ($N_\mu > 4$) reconstructed in the ALICE Time Projection Chamber (TPC).

In similar experiments at LEP, ALEPH and DELPHI [2, 3] were able to successfully describe the muon multiplicity distribution (MMD) using standard hadronic interaction models. However, the highest multiplicity events ($N_\mu > 75$), occurred with a rate that was almost an order of magnitude above the expectation.

In ALICE we exploit the large size and excellent tracking capability of the TPC [4] to study the muonic component of the EAS. We describe the analysis of the MMD, with particular



emphasis on high muon multiplicity (HMM) events, which we define as those with $N_\mu > 100$ corresponding to an areal density $\rho_\mu > 5.9 \text{ m}^{-2}$. The hadronic interaction model QGSJET, commonly used in EAS simulations, was chosen to describe the showers [5, 6].

2. ALICE configuration for cosmic-ray physics

The ALICE detector is located in a cavern 52 m underground with 28 m of overburden rock. The rock absorbs all of the electromagnetic and hadronic components of the observed EAS, so that only muons with an energy $E \geq 16 \text{ GeV}$ at the surface reach detectors [7]. A complete description of the apparatus is given in [1].

The TPC was used to reconstruct the trajectory of cosmic-ray muons passing through the active volume. Three additional detectors were used as triggers for this study: ACORDE (Alice COsmic Ray DETector), TOF (Time Of Flight Detector) and SPD (Silicon Pixel detector). ACORDE is an array of 60 scintillator modules located on the three top octants of the ALICE magnet, covering a 10% of its surface area. A trigger is formed by the coincidence of signals in n different modules (n -fold coincidence). The SPD is part of the Inner Tracking System located inside the inner field cage of the TPC. It is composed of two layers of silicon pixel modules centred upon the nominal interaction point of the LHC beams. The SPD was incorporated into the trigger by requiring a coincidence between signals in the top and bottom halves of the outermost layer. The TOF is a cylindrical array of multi-gap resistive-plate chambers that completely surrounds the outer radius of the TPC. The TOF trigger requires a signal in a pad corresponding to a cluster of readout channels covering an area of 500 cm^2 in the upper part of the detector and another signal in a pad in the opposite lower part forming a back-to-back coincidence with respect to the central axis of the detector.

Given the complementary coverage of the TOF barrel to the TPC, the TOF trigger is the mainly responsible for selecting events in the low-to-intermediate range of muon multiplicities ($7 \leq N_\mu \leq 70$). The efficiency of TOF and ACORDE has an increasing trend with the muon multiplicity. Both triggers reach full (100%) efficiency for $N_\mu > 10$ (TOF) and $N_\mu > 15$ (ACORDE). SPD makes only a minor contribution to the MMD in the low-to-intermediate range of muon multiplicities.

The trajectory of cosmic-ray muons traversing the TPC is typically reconstructed as two separated tracks, one in the upper half (*up*) and the other in the lower half (*down*) of the TPC. A specific algorithm for cosmic muons was developed to match each *up* track with its corresponding *down* track to reconstruct the full trajectory of the muons and to eliminate double counting. High-multiplicity Monte Carlo events have been used to optimise the matching performance. To avoid reconstruction inaccuracies associated with the most inclined showers we restricted the zenith angle of all events to the range $0^\circ < \theta < 50^\circ$.

3. Atmospheric-muon multiplicity distribution

The measured MMD corrected for trigger efficiency is shown in Fig. 1 [8]. Values for the systematic uncertainty in the number of events as a function of multiplicity have been estimated by varying the parameters of the track reconstruction and matching algorithms. We find a smooth distribution up to a muon multiplicity of around 70 and then 5 HMM events. The MMD obtained in ALICE is similar to the multiplicity distribution reported in the past by experiments at LEP, but those experiments did not provide any satisfactory explanation for the HMM events. The aim of our analysis is to reproduce the MMD with more recent hadronic-interaction models to describe the EAS and to explore the origin of the HMM events and in particular its rate.

The experimental rate of the HMM events is $1.9 \times 10^{-6} \text{ Hz}$ with a statistical uncertainty of 45%, giving an error in the rate of $\pm 0.9 \times 10^{-6} \text{ Hz}$.

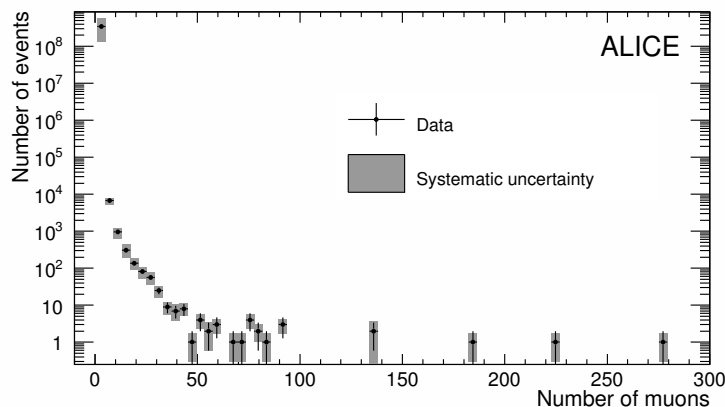


Figure 1. The muon multiplicity distribution of the whole sample of data (2010-2013) corresponding to 30.8 days of data taking [8].

4. Monte Carlo studies

The difficulty in describing EAS, and consequently the number of muons reaching ground level, mainly arises from uncertainties in the properties of multi-particle production in hadron-air interactions. These interactions are often described phenomenologically within Monte Carlo event generators.

In this study we have adopted the CORSIKA [9] event generator incorporating QGSJET [5] for the hadronic interaction model to simulate the generation and development of EAS. CORSIKA version 6990 incorporating QGSJET II-03 has been used to study the MMD distribution and HMM events; CORSIKA version 7350 incorporating QGSJET II-04 has been used to check and confirm the results for HMM events. The significant differences between the two versions of QGSJET are the inclusion of Pomeron loops in the formalism of QGSJET II-04 and a retuning of the model parameters using early LHC data for the first time [10].

When generating cosmic-ray events, the core of each shower was scattered randomly at ground level over an area covering $205 \times 205 \text{ m}^2$ centred upon the nominal LHC beam crossing point.

The first step in the analysis was to attempt to reproduce the measured MMD in the low-intermediate range of multiplicity ($7 \leq N_\mu \leq 70$). Samples of proton and iron primary cosmic rays were generated in the energy range $10^{14} < E < 10^{18} \text{ eV}$ and with zenith angles in the interval $0^\circ < \theta < 50^\circ$. The pure proton sample provides a lower limit on the number of events for a given multiplicity, representing a composition dominated by light nuclei, while a pure iron sample provides an upper limit, representing a composition dominated by heavy nuclei. A typical power law energy spectrum, $E^{-\gamma}$, has been adopted with a spectral index $\gamma = 2.7 \pm 0.03$ for energies below the knee ($E_k = 3 \times 10^{15} \text{ eV}$) and $\gamma_k = 3.0 \pm 0.03$ for energies above the knee. The total (all particle) flux of cosmic rays was taken from [11]. The flux was estimated to be $F(1 \text{ TeV}) = 0.225 \pm 0.005 (\text{m}^2 \text{ s sr TeV})^{-1}$.

We generated simulated events equivalent to 30.8 days live time to permit direct comparison with the data without the need to apply an arbitrary normalisation factor. A comparison of the trigger corrected, measured MMD with the simulations is shown in Fig. 2. For ease of comparison, the points obtained with the simulations were fitted with a power-law function to obtain the curves for proton and iron.

At lower multiplicities, corresponding to lower primary energies, we find that the data approach the proton curve, while higher multiplicity data lie closer to the iron curve, behaviour consistent with several previous experiments at ground level. The limited statistics in the range

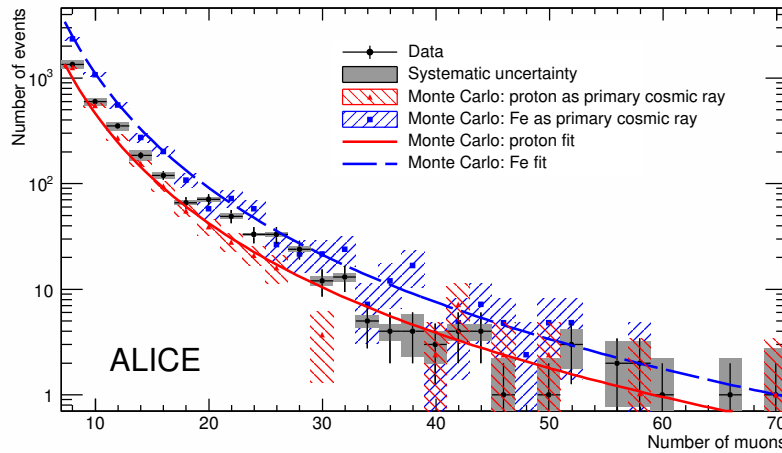


Figure 2. The measured muon multiplicity distribution compared with the values and fits obtained from CORSIKA simulations. The errors are shown separately (statistical and systematic) for data, while for Monte Carlo they are the quadrature sum of the statistical and systematic uncertainties [8].

$N_\mu > 30$ does not allow any conclusion above this multiplicity.

The errors in Fig. 2 are shown separately (statistical and systematic) for data, while for Monte Carlo they are the quadrature sum of the statistical and systematic uncertainties. The systematic errors in the simulations take into account uncertainties in the flux of cosmic rays at 1 TeV, the slope of the energy spectrum below and above the knee, the description of the rock above the experiment and the uncertainty in the the number of days of data taking (detector live time).

The frequency of HMM events ($N_\mu > 100$) was studied with the same simulation framework used to study the MMD in the intermediate range of multiplicities ($7 \leq N_\mu \leq 70$). The aim was to compare the rate of HMM events obtained from simulations to the measured rate. Since these are particularly rare events, a very high statistics sample of simulated events was required to permit a meaningful quantitative comparison. Consequently we have simulated a live time equivalent to one year. With a simplified Monte Carlo as a first step, we determined that only primaries with energy $E > 10^{16}$ eV contribute to these events. Therefore, only events in the range of primary energy $10^{16} < E < 10^{18}$ eV have been generated to achieve an equivalent of 365 days exposure for both proton and iron primaries.

In Table 1 we present the results [8] of this analysis where we compare the rate of simulated HMM events with the measured rate.

We note that the pure iron sample simulated with CORSIKA 7350 and QGSJET II-04 produces a HMM event rate in close agreement with the measured value. The equivalent rate obtained with CORSIKA 6990 and QGSJET II-03 is lower, although still consistent with the measured rate. The difference between the two simulations comes primarily from the hadronic model used to generate the EAS. It is more difficult to reconcile the measured rate of HMM events with the simulated rate obtained using proton primaries, independent of the version of the model. However, the large uncertainty in the measured rate prevents us from drawing a firm conclusion about the origin of these events, although heavy nuclei appear to be the most likely candidates.

HMM events	CORSIKA 6990 QGSJET II-03		CORSIKA 7350 QGSJET II-04		Data
	proton	iron	proton	iron	
Period [days per event]	15.5	8.6	11.6	6.0	6.2
Rate [$\times 10^{-6}$ Hz]	0.8	1.3	1.0	1.9	1.9
Uncertainty (%) (syst + stat)	25	25	22	28	49

Table 1. Comparison of the HMM event rate obtained with the full simulation and from measurement.

5. Conclusions

In the period 2010 to 2013, ALICE acquired 30.8 days of dedicated cosmic ray data recording approximately 22.6 million events containing at least one reconstructed muon. Comparison of the measured muon multiplicity distribution with an equivalent sample of Monte Carlo events suggests a mixed-ion primary cosmic ray composition with an average mass that increases with energy. The MMD measured with ALICE is in agreement with most experiments working in the energy range of the knee.

Over the 30.8 days of data taking, 5 events with more than 100 muons and zenith angles less than 50° have been recorded with ALICE. We have found that the observed rate of HMM events is consistent with the rate predicted by CORSIKA 7350 using QGSJET II-04 to model the development of the resulting EAS, assuming a pure iron composition for the primary cosmic rays. Only primary cosmic rays with an energy $E > 10^{16}$ eV were found to give rise to HMM events. This observation is compatible with a knee in the cosmic ray energy distribution around 3×10^{15} eV due to the light component followed by a spectral steepening, the onset of which depends on the atomic number (Z) of the primary.

This is the first time that the rate of HMM events, observed at the relatively shallow depth of ALICE, has been satisfactorily reproduced using a conventional hadronic model for the description of extensive air showers; an observation that places significant constraints on alternative, more exotic, production mechanisms.

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