#### Muon bundles from cosmic rays with ALICE

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ALICE, a general purpose experiment designed to investigate nucleusnucleus collisions at the CERN Large Hadron Collider (LHC), has also been used to detect atmospheric muons produced by cosmic-ray interactions in the atmosphere.

In this contribution the analysis of the multiplicity distribution of the atmospheric muons detected by ALICE between 2010 and 2013 is presented, along with a comparison with Monte Carlo simulations. Special emphasis is given to the study of high-multiplicity events, i.e. those containing more than 100 reconstructed muons. Such high-multiplicity events demand primary cosmic rays with energy above  $10^{16}$  eV. The frequency of these events can be successfully described by assuming a heavy mass composition of primary cosmic rays in this energy range, using the most recent interaction models to describe the development of the air shower resulting from the primary interaction.

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### 1 Introduction

The use of collider detectors to study the atmospheric muons was pioneered by the LEP experiments ALEPH, DELPHI and L3. All results reported by the LEP experiments were consistent with the standard hadronic interaction models, except the observation of high-multiplicity muon-bundle events: even under the assumption of the highest measured flux and a pure-iron spectrum, the Monte Carlo models of that time failed to describe the rate of those high-multiplicity events [1],[2].

ALICE (A Large Ion Collider Experiment) [3] is a general-purpose, heavy-ion detector at the CERN LHC. It focuses on the study of the properties of the Quark-Gluon Plasma (QGP) created in strongly interacting matter at extreme energy densities in high energy nucleus-nucleus collisions. Besides the study of heavy-ion physics, since 2009 ALICE developed a cosmic-ray physics program, which exploits the excellent tracking capabilities of the Time Projection Chamber (TPC) to detect and reconstruct the muons produced by the cosmic radiation interacting with the atmosphere.

ALICE is located at Point 2 of the LHC tunnel, 52 m underground and with 28 m of overburden rock. This depth of rock completely absorbs the electromagnetic and hadronic components of the cosmic-ray induced air shower, and poses an energy threshold of 16 GeV for vertical muons [4]. The ALICE solenoid magnet (maximum strength 0.5 T) houses the central-barrel detectors, where different techniques are exploited to detect and reconstruct all particles coming out from the primary interaction vertex. A forward muon arm, is located on one side outside the solenoid magnet. A detailed description of the ALICE detector is given in [3].

For the cosmic-ray data taking three detectors were used for the trigger. The Alice COsmic Ray DEtector (ACORDE) is an array of 60 scintillator modules located on the three top octants of the ALICE magnet, covering 10% of their surface. The Silicon Pixel Detector (SPD) forms the two innermost coaxial cylinders of the Inner Tracking System (ITS) around the beam pipe and it is composed by 10M pixels segmented into 120 modules; for cosmic studies it can provide a trigger. The Time Of Flight (TOF) detector is a cylindrical array of 1638 Multi-gap Resistive Plate Chamber pads arranged in 18 sectors, surrounding the TPC; the trigger configuration used for the present analysis requires a coincidence between a signal in a sector of the upper part and a signal in a sector in the opposite lower part.

The ALICE Time Projection Chamber (TPC) is the largest detector of this type, and is the main ALICE tracking device. It has an inner radius of 80 cm, an outer radius of 280 cm and a total length of 500 cm along the beam axis. Filled with a mixture of Ne-CO<sub>2</sub>-N<sub>2</sub>, it is read out by multi-wire proportional chambers at both end caps. The total area to detect cosmic muons is about 26 m<sup>2</sup>, however after applying a minimum length requirement to the reconstructed muon tracks the effective area reduces to about 17 m<sup>2</sup>.

### 2 Data selection and reconstruction

The data used for the cosmic-ray analysis presented here [5] were collected between 2010 and 2013 during periods without circulating beams in the LHC. Cosmic-ray data were recorded with a logical OR of at least two out of the three aforementioned triggers, depending on the run period. The integrated live time amounts to 30.8 days, during which  $\sim$ 22.6M events with at least 1 reconstructed muon in the TPC were accumulated. A multi-muon event is defined as an event with at least 5 muons; the data sample contains 7487 multi-muon events.

The TPC tracking algorithm was designed to reconstruct tracks coming out from the interaction region, working inwards from the outer radius. As a consequence a cosmic muon crossing the TPC gets reconstructed as two separate tracks, called *up* and *down*, belonging to the two halves of the TPC cylinder. A specific algorithm was worked out to match the two track segments as a single one. Real and Monte Carlo events of different multiplicities were used to optimize the parameters of this matching algorithm. Moreover, to avoid possible reconstruction inaccuracies associated with the most inclined tracks, the zenith angle of all accepted tracks was restricted to  $0 < \theta < 50^{\circ}$ .

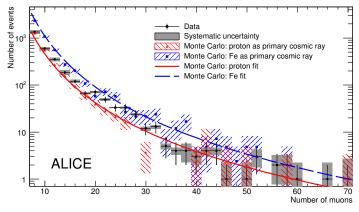
TPC tracks were required to consist of at least 50 clusters (out of a maximum of 159) and, in events where the magnetic field was on, to have a minimum momentum of 0.5 GeV/c, to eliminate all possible background from  $e^{\pm}$ . For multi-muon events a parallelism condition was also applied, which requires the angular difference in space between two tracks to satisfy  $\cos \Delta \psi > 0.990$ . Finally, to match up and down tracks a maximum distance of closest approach of 3 cm in the TPC middle plane was imposed. A muon reconstructed with two TPC tracks (up and down) is called a *matched muon*; a track satisfying all selection criteria but the maximum distance is still accepted as muon candidate but flagged as *single-track muon*. Most single-track muons are particles crossing the TPC near the edges where part of their trajectory may fall outside the sensitive volume.

# 3 Muon multiplicity distribution

The main topic related to the cosmic-ray physics investigated by ALICE is the study of the muon-multiplicity distribution (MMD). The MMD, obtained from the whole data sample and corrected for trigger efficiency, shows a smooth distribution up to a muon multiplicity of ~ 70 and then 5 events with a multiplicity greater than 100. Events with  $N_{\mu} > 100$  are denoted High Muon Multiplicity (HMM) events.

In order to understand the MMD, simulated events equivalent to 30.8 days of live time were generated using CORSIKA [6] as event generator and QGSJET [7] for the hadronic interaction model. Two samples, pure p (representing a light composition) and pure Fe (representing an extremely heavy composition), were generated. The primary cosmic-ray energy was restricted to the interval  $10^{14} < E < 10^{18}$  eV following the usual power law energy spectrum  $E^{-\gamma}$ , with a spectral index  $\gamma = 2.7$  below the knee ( $E_k = 3 \times 10^{15}$  eV) and  $\gamma = 3.0$  above. The total all-particle absolute flux was extracted from [8]. For each shower the core was randomly scattered at surface level over an area of  $205 \times 205$  m<sup>2</sup> centered above ALICE.

The comparison between the MMD in the range  $7 < N_{\mu} < 70$  and the simulated distribution fitted with a power-law function is shown in Fig. 1 [5], where errors are shown separately (statistical and systematic) for data, and summed in quadrature for Monte Carlo. Below  $N_{\mu} \sim 30$  the data, as expected, are between the pure p composition (approaching it at low multiplicity) and the pure Fe composition (at higher multiplicity). Above  $\sim 30$  the low statistics does not allow us to draw any firm conclusion, though the experimental points, considering their errors, are inside the region limited by the p and Fe curves.



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Figure 1: Measured MMD compared with values and fits obtained from simulations with p and Fe primaries. Figure taken from [5].

### 4 High muon multiplicity events

In 30.8 live days 5 HMM events were recorded, corresponding to a rate of  $1.9 \times 10^{-6}$  Hz. The highest multiplicity cosmic-muon event reconstructed in the TPC was found to contain 276 muons. To estimate the rate of these events, while limiting the fluctuations in the number of HMM simulated events, a live time equivalent of 1 year was simulated. The full simulation was restricted to primaries with  $10^{16} < E < 10^{18}$  eV, since only primaries within this energy range contribute to these events. To further reduce the statistical fluctuations, four additional simulations were performed, reusing the same EAS sample and randomly varying the shower core in the 205×205 m<sup>2</sup> area. Given that the TPC acceptance is some 3000 times smaller, this ensures that the samples are statistically independent. By averaging the 5 samples the number of

HMM events in 1 year is estimated while reducing the statistical fluctuations.

In Tab. 1 [5] the results from Monte Carlo simulations are compared with data. The rate of HMM events can be well reproduced by the latest interaction models and a primary flux extrapolated from the direct measurements at 1 TeV. A pure Fe primary composition seems in closer agreement with the measured rate, though the large uncertainty of the latter prevents a definite conclusion about the origin of these events. This is consistent with the fact that HMM events stem from primaries with energy  $> 10^{16}$  eV, where the composition is expected to be dominated by heavier elements.

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

Table 1: Comparison of the HMM event rate between data and Monte Carlo [5].

### 5 Conclusions

In 2010–2013 the ALICE Experiment collected 30.8 live days of cosmic-ray data. The MMD distribution at low and intermediate multiplicities is well reproduced by Monte Carlo simulations using CORSIKA with the QGSJET model. The measurements by ALICE presented here suggest a mixed ion primary cosmic-ray composition with an average mass increasing with energy. In the same period 5 HMM events were recorded. The observed rate is consistent with the predictions of the most recent CORSIKA and QGSJET models using a pure Fe primary composition and energies  $> 10^{16}$  eV. For the first time the rate of HMM events has been well reproduced using conventional hadronic interaction models and a primary flux extrapolated from low energies.

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