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High-multiplicity muon events observed with EMMA array

High-multiplicity muon events observed with EMMA array

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Abstract. High-multiplicity data, collected with a segmented scintillator array of the cosmic-ray experiment EMMA (Experiment with Multi-Muon Array), is presented for the first time. The measurements were done at the depth of 75 meters (210 m.w.e.) in the Pyhäsalmi mine in Finland. EMMA uses two types of detectors: drift chambers and plastic scintillation detectors. The presented data were acquired over the period between December, 2015 and April, 2018 using 128–800 plastic scintillator pixels probing the fiducial area of $\sim$100 m^2. The results are being interpreted in terms of CORSIKA simulations. Several events with densities in excess of 10 muons per m^2 were observed. At the next stage of the analysis, the high-multiplicity events will be matched with precision tracking data extracted from the multi-layer drift chambers of EMMA. Observation of high-density muon bundles was first reported by the LEP experiments: DELPHI, L3+C, and ALEPH. More recently, the ALICE experiment at CERN has provided new cosmic-ray results together with improved interpretation benefiting from the updated cross section values extracted from LHC results. While the tracking performance of ALICE is superior to EMMA, the duration of ALICE cosmic-ray measurements is very limited. Over the period of 2010–2018 the total exposure was only 93 days while EMMA, having a similar overburden provides a larger footprint and collects data continuously.

1. Introduction

Upon reaching the upper layers of the atmosphere, high-energy cosmic rays collide with nuclei generating extensive air showers (EAS) cascading towards the Earths surface and spreading over the area of several square kilometers. By measuring the particle flux at the ground level or/and by registering Cherenkov light emitted by EAS components traversing the atmosphere, it is possible to deduce the direction and energy of the primary cosmic ray (CR) and even approximate its rest mass. Experiments based on this approach are, for example, the Pierre Auger Observatory [1] in the Argentinian Pampas, the already decommissioned Kascade Grande [2] array or the LHAASO [3] project being constructed on the Tibetan Plateau. The key characteristic of these setups is the large fiducial area required to probe an adequate sample of the EAS footprint and to compensate for the very low rate of high-energy CR. The steep, power-law drop in intensity as a function of energy is also the main reason why direct measurements cannot reach the highest energies including the interesting region between 1 and 10 PeV associated with the so-called knee.

However, there are other approaches. Already the simplest, binary description of the development of EAS cascade indicates that the most energetic particles of the shower are created at the earliest interaction stages. By filtering out all the other components of EAS one would still retain information about the key characteristics of the primary CR. This is the essence of underground measurements. The overburden transmits only the hardest muons to the detection array below the ground. The additional bonus of this approach is a considerably smaller footprint as the energetic muons are strongly kinematically focused in the direction of the primary CR.

2. EMMA experiment

The EMMA (Experiment with Multi-Muon Array) [4] is located at the depth of 75 m at the Pyhäsalmi mine in Finland. The average overburden of 210 m.w.e. corresponds to the cutoff energy of 50 GeV for vertical muons. The underground infrastructure consists of a network of eleven stations equipped with multi-layer, position-sensitive detectors intended to detect muon showers, their direction and density distribution. This information is used to reconstruct the core position, deduce the energy of the primary CR, and its approximate mass number.

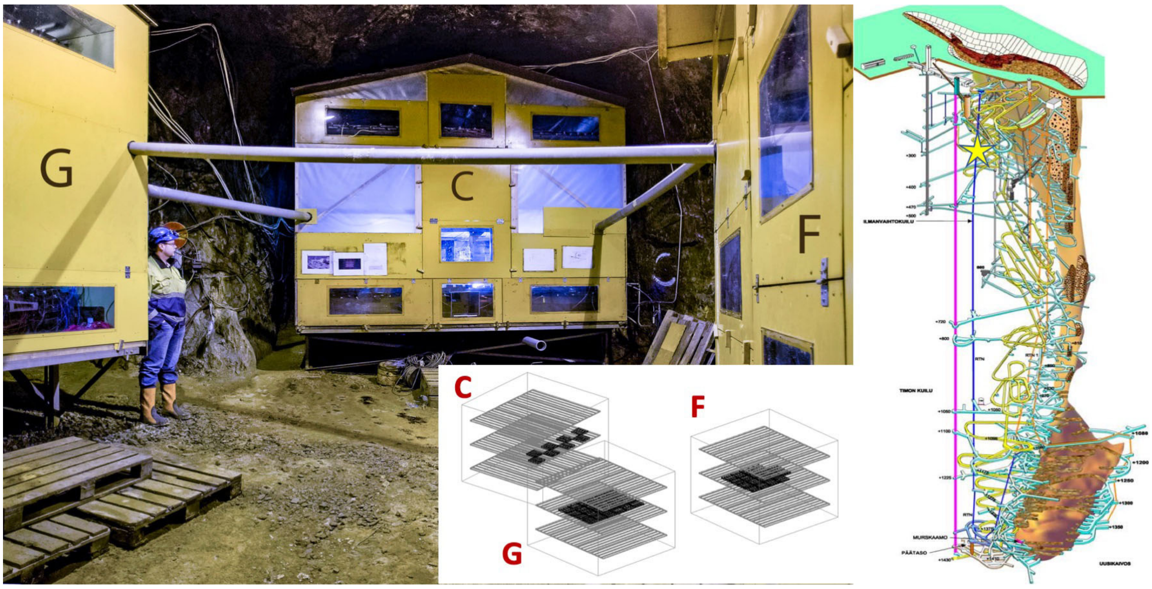

Figure 1. Photo of the central tracking stations of EMMA. Positions of the scintillator modules inside of the stations are marked black in the central inset. The yellow star on the right inset indicates the approximate location of EMMA on a 3D depiction of the mine.

The primary detectors for EMMA are gas-filled drift chambers [4]. While they have excellent position resolution, significant correction factors have to be used to account for efficiency loss in case of high-density events. To improve the performance and sensitivity of EMMA for such events and to determine and monitor the efficiency of the drift chambers as a function of multiplicity, we have designed and built a dedicated array of high-granularity scintillator modules optimized for the detection of energetic muons [4]. The building block of the array is a SC16 module consisting of 16 individual scintillator pixels, $122 \times 122 \times 30$ mm^3, tightly arranged as a flat 4×4 matrix housed in a 0.5×0.5 m^2 steel box. Recently, SC16s were successfully used [5] to measure the flux and angular distribution of the muons.

Because of a significantly higher cost per square meter of the active area, the coverage with scintillators is restricted to the central parts of EMMA tracking stations (see Fig. 1). Nevertheless, before the full data analysis is completed, it is possible to treat the scintillator array as an independed detector system capable of registration of high-multiplicity events without the need of extensive efficiency correction procedure. The obvious disadvantage of this approach is the reduction of the fiducial area.

3. CORSIKA and GEANT4 simulations

The key parameters of the primary CR particle to be deduced from the measured characteristic of the shower particles are energy, rest mass and the arrival direction. The latter is straightforward. The angular spread of muons detected at the EMMA level is of the order of 3 degrees. To reconstruct muon trajectories, it is sufficient to rely on the known detector properties. Determination of the shower core and muon density distributions is already less reliable because of the limited and non-hermetic coverage. As seen in Fig. 1, there is a large non-instrumented area between the measuring stations and around the detectors inside the stations. Nevertheless, the position of the core and the density distribution may be extracted from relatively straightforward fits. To go beyond that and determine the energy and the rest mass of the initial CR, one has to rely on interaction and transmission models and have a good knowledge about the structure of the overburden above the measuring stations.

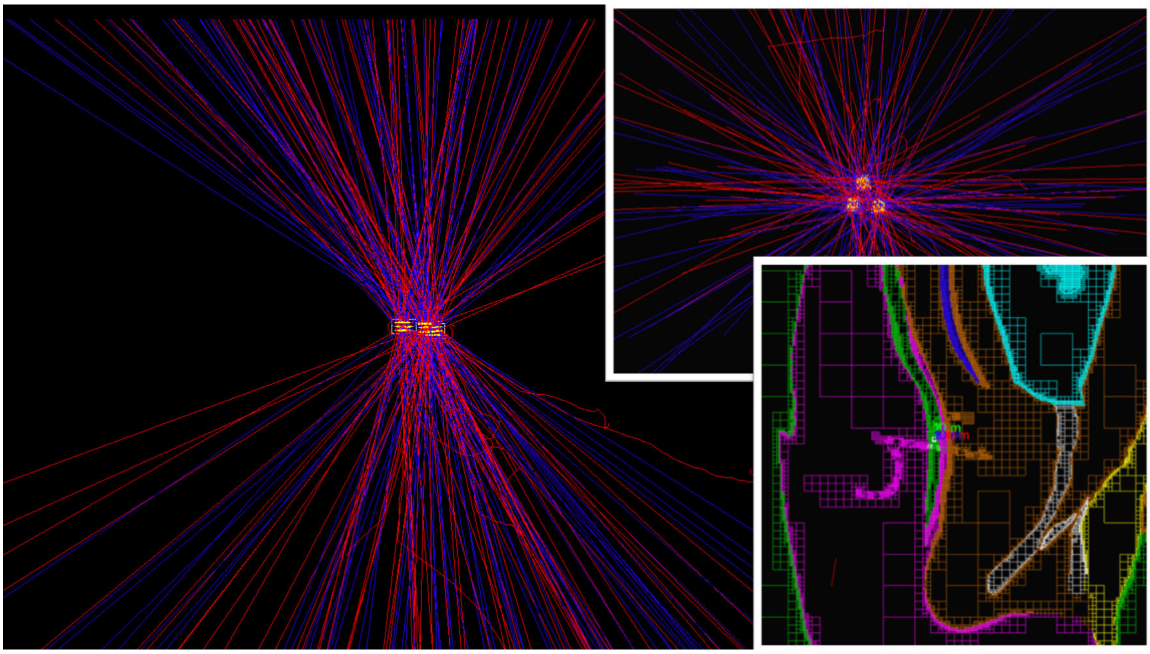

Figure 2. Example of EMMA simulations based on CORSIKA. Red trajectories are for negative particles and blue for positive. The bright spots indicate hits inside the active volume of EMMA detectors. Side view is on the left; top view is on the upper right inset. The bottom right inset shows the model of the upper layers of the mine implemented into GEANT4.

Fortunately, predictions of different hadronic interaction models are consistent although inclusion of the LHC cross section data did increase the yield of energetic muons. Our latest simulations use CORSIKA and QGSJETII-04 (see Fig. 2). Compared to the pre-LHC models, e.g. QGSJET-01C, we get approximately 8±3% and 11±3% larger muon yields for 4 and 40 PeV proton showers, and 7±1% and 9±1% for 4 and 40 PeV iron showers [6].

4. First results

The central stations of the EMMA experiment have been collecting data for 900 days. Scintillator arrays totaling 800 pixels were added to the middle level of the stations during the second part of the measurement. In station C, 128 pixels collected data for 558 days. In F, 288 pixels for 427 days. In G, 384 pixels for 310 days. The left side of Fig. 3 shows the count rate per hour for each scintillator subset. The right side shows the coincidence spectrum obtained by requiring the presence of at least one muon in each station. The displayed data correspond to the effective running time of 305 days. The plotted multiplicity values are preliminary.

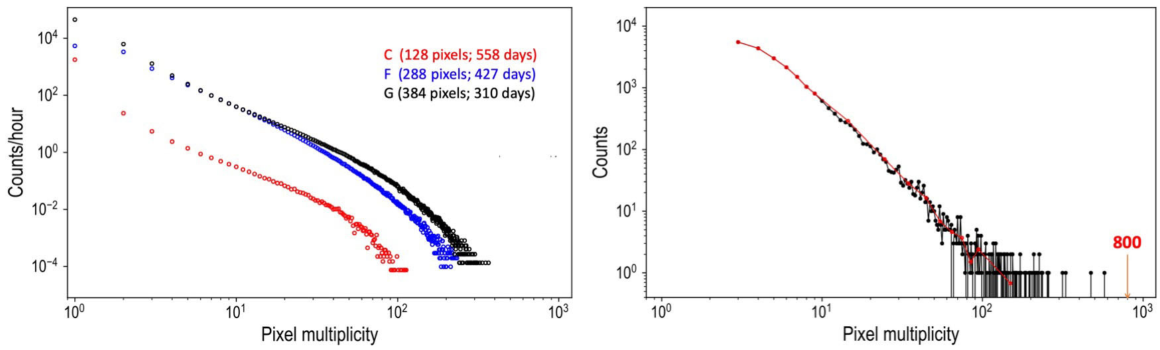

Figure 3. Left: count rate per hour registered by the scintillator arrays in station C (red points), F (blue points), and G (black points). Right: multiplicity spectrum of the EMMA scintillation array operating in coincidence. Logarithmically smoothed results are plotted in red. The maximum observed multiplicity was 580.

5. Summary

High-multiplicity events are of special interest because they result from showers induced by high-energy CR. Observations of high-density muon bundles were first reported by the LEP experiments: DELPHI, L3+C, and ALEPH. At that time, there was a tension between the measured intensities and model predictions. More recently, the ALICE experiment at CERN has provided new results with simulations benefiting from the latest LHC cross section data [7]. While the agreement with the predictions has improved, the high-multiplicity data is still not sufficient for definite conclusions. In particular, distinction between the proton- and iron-induced showers cannot be made. In that respect, with ten times longer exposure, two and a half times larger detector footprint and a fiducial/sampling area of 100 m^2, EMMA should provide a clear improvement.

References

[1] Pierre Auger Collaboration 2019 *Front. Astron. Space Sci.* 6:24
[2] Apel W, *et al.* 2010 *Nucl. Instrum. Meth.* A **620** 202
[3] Bai X *et al.* 2019 arXiv:1905.02773v1
[4] Kuusiniemi P *et al.* 2018 *Astroparticle Physics* **102** 67
[5] Trzaska W H *et al.* 2019 *Eur. Phys. J.* C **79** 721
[6] Sarkamo J 2014, Oulu Univ. Press, PhD. thesis. Rep. Ser. in Phys. Sciences, No. 92
[7] ALICE Collaboration 2016, JCAP01 032