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**Title:** EAS selection in the EMMA underground array

**Year:** 2013

**Version:**

**Please cite the original version:**

Sarkamo, J., Bezrukov, L., Enqvist, T., Fynbo, H., Inzhechik, L., Joutsenvaara, J., Kalliokoski, T., Kuusiniemi, P., Loo, K., Lubsandorzhiev, B., Monto, T., Petkov, V., Räihä, T., Slupecki, M., Trzaska, W., & Virkajärvi, A. (2013). EAS selection in the EMMA underground array. In 23rd European Cosmic Ray Symposium (and 32nd Russian Cosmic Ray Conference) 3–7 July 2012, Moscow, Russia. Institute of Physics. Journal of Physics: Conference Series, 409. <https://doi.org/10.1088/1742-6596/409/1/012086>

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2013 J. Phys.: Conf. Ser. 409 012086

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## EAS selection in the EMMA underground array

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**Abstract.** The first measurements of the Experiment with MultiMuon Array (EMMA) have been analyzed for the selection of the Extensive Air Showers (EAS). Test data were recorded with an underground muon tracking station and a satellite station separated laterally by 10 metres. Events with tracks distributed over all of the tracking detector area and even extending over to the satellite station are identified as EAS. The recorded multiplicity spectrum of the events is in general agreement with CORSIKA EAS simulation and demonstrates the array's capability of EAS detection.

### 1. Introduction

Primary cosmic-rays above the energy of  $10^{15}$  eV are studied by measuring the properties of the Extensive Air Showers (EAS). Several experiments (see, for example, ref. [1]) using various measurement methods have reported an increase in the average mass of the primary particles in the energy range of  $10^{15} - 10^{16}$  eV.

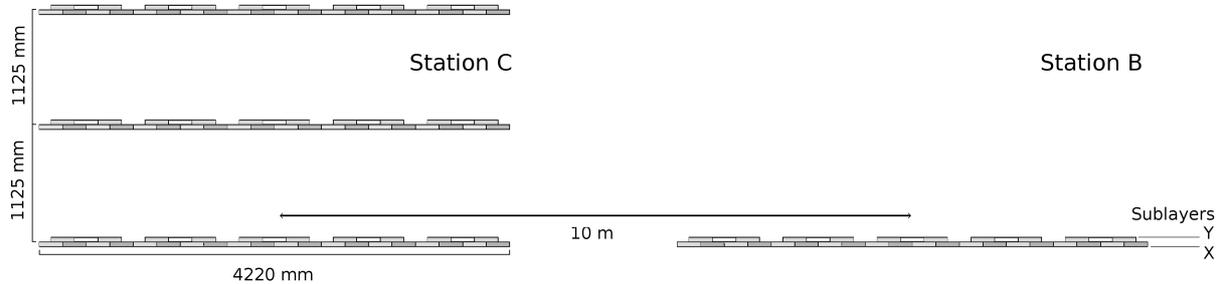
A novel approach to the study of the primary spectrum and mass composition is the measurement of the high-energy muon lateral density distribution of EAS. The Experiment with MultiMuon Array (EMMA) [2] is an underground EAS array designed for the measurement of the high-energy muon component ( $E_{\mu} > 50$  GeV). It consists of several muon tracking detectors at the depth of 75 metres (210 m.w.e) in the Pyhäsalmi Mine, Finland (63°39.6 N, 26°02.5 E).

This contribution focuses on the results of 2011 test data taking. The data, taken with two stations of the array, have been analyzed for the selection of EAS events from all the recorded events. The presented methods are an essential progress towards the analysis of the primary cosmic-ray spectrum by the experiment.

### 2. Measurement configuration and data taking

Two underground detector stations were used in the data taking. Station C is a muon tracking detector with the active dimensions of  $4220 \times 3650 \times 2250$  mm<sup>3</sup> and a geometric acceptance of 18 sr m<sup>2</sup> for three-layer tracking. It consists of 105 drift chambers of the former DELPHI [3]

experiment. Station B is a prototype one-layer station. The horizontal distance between the station centres is 10 metres. The configuration is depicted in figure 1.



**Figure 1.** A schematic view of the measurement configuration in the data taking. The chamber configuration of Station C is depicted on the left side. The right side shows Station B. Individual chambers are indicated by shaded rectangles. The sublayers within a layer are referred to as  $X$  and  $Y$ . The chamber heights (20 mm) are exaggerated for clarity. The lengths of the chambers are 3650 mm. Other dimensions are indicated in the figure.

DAQ and trigger electronics are situated inside the stations. Signals are exchanged between the stations via cable canals running in the cavern. HV is supplied separately within the stations. Ar:CO<sub>2</sub>-gas mixture is delivered from a surface supply. The anode and delay line signals from the chambers are read out by CAEN V767b TDCs and the charged particle coordinates can be extracted from the recorded signals. The trigger is generated from the chamber anode signals. In the data taking, a trigger input generated from Station C was a triple-coincidence between any chambers from the three separate layers. The trigger input from Station B was a coincidence of any chambers from the separate  $X$ - and  $Y$ - sublayers. The final trigger was OR of the Station C and Station B inputs. This trigger logic was used to guarantee efficient recording for the muon events. Given a relatively high singles rate from the chambers ( $\sim 100$  Hz per chamber) and the coincidence gate widths ( $5\mu\text{s}$ ), not all triggers correspond to muon events.

Test data for the analysis were taken from 13th April to 4th June 2011 for an effective period of 44.0 days. In total, 184 million triggers were recorded, out of which the EAS can be extracted.

### 3. EAS extraction

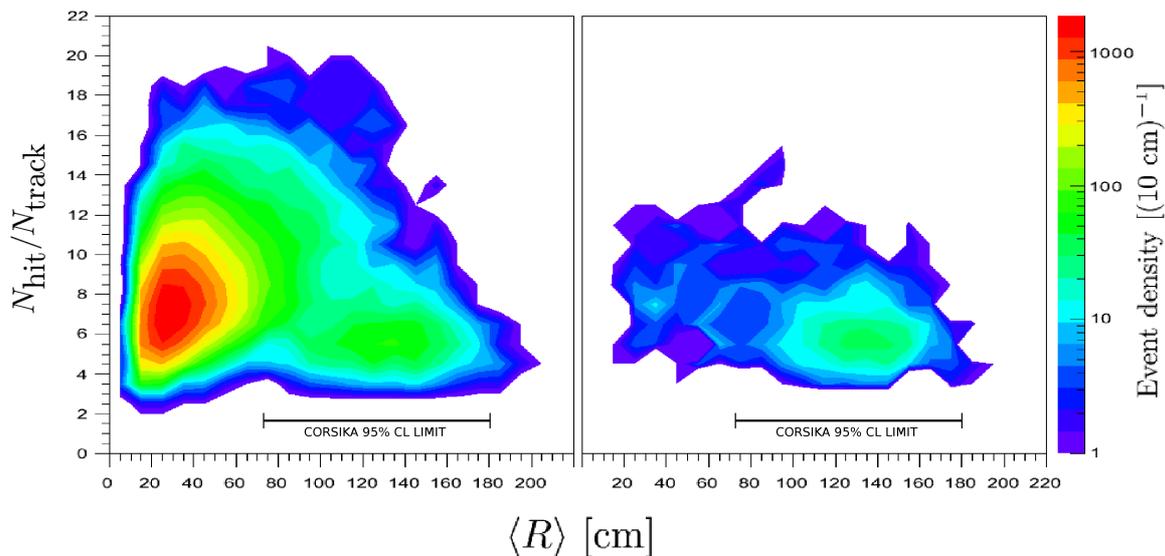
The track reconstruction relies on an algorithm of hit extraction and track fitting through the hits. A hit is defined as an extracted avalanche coordinate within the detector. The position accuracy of the detector is  $\sim 1$  cm<sup>2</sup>. The tracks are reconstructed using the extracted hit positions and a parallelity ( $\delta\theta < 3^\circ$ ) criterion. Some hits are left with no corresponding track. The shower arrival direction is determined as an average of the track arrival directions.

A study of multiple-track events recorded by Station C reveals that two classes of events exist. Some events consist of tightly clustered hits and tracks localized well within the detector area. Other events consist of hits and tracks which are more uniformly distributed over all of the detector area.

Two variables are used to classify the multiple-track events. The bundle size is defined as  $\langle R \rangle = \sum_{i=1}^{N_{\text{track}}} r_i / N_{\text{track}}$ , where  $N_{\text{track}}$  is the number of tracks and  $r_i$  are the distances between the individual tracks and the mass centre of all the tracks in the event. The distance is calculated on the detector plane. The value of the bundle size is affected by the detector dimensions and the expectation value is  $\sim 150$  cm for uniformly distributed tracks. The 'purity' of the event reconstruction is described by  $P = N_{\text{hit}} / N_{\text{track}}$ , where  $N_{\text{hit}}$  is the

number of reconstructed hit coordinates. The value of  $P$  is expected to be larger for events with accompanying electromagnetic subshowers in comparison to pure muon events.

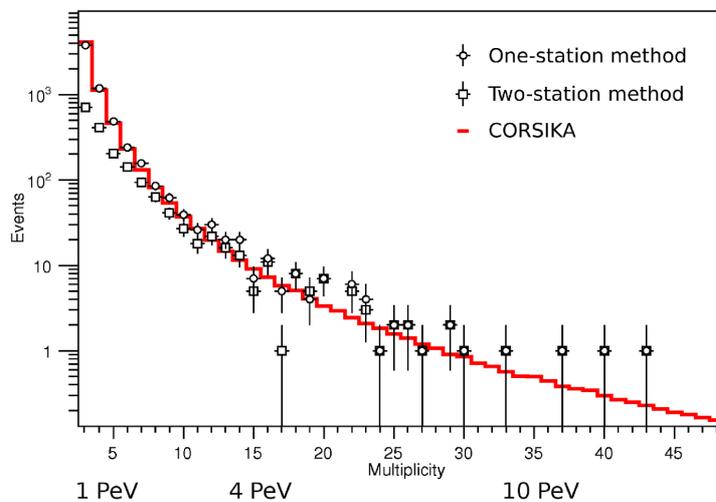
One parametre is used in the case of Station B.  $N^B$  is defined as the number of hit pairs recorded by the station. A hit pair is counted given that  $|\bar{z}_X - \bar{z}_Y| < 10$  cm, where  $\bar{z}_i$  are the hit positions recorded in the  $X$ - and  $Y$ - layers of the station.



**Figure 2.** The event distribution in the  $(\langle R \rangle, P)$ -plane for one array station (left panel) and two array station (right panel) analyses. The cuts used are:  $N_{\text{track}} > 4$  (one station),  $N_{\text{track}} > 4$  and  $N^B > 0$  (two stations). The binning of  $x$ -axis is in units of 10 cm and in  $y$ -axis in units of 1. The number of events in indicated by colours. The horizontal bars express the CORSIKA expectation for  $\langle R \rangle$  for the multiplicity of 5.

Figure 2 depicts the event distributions of Station C in the  $(\langle R \rangle, P)$ -plane. Events with reconstructed zenith angles  $< 35^\circ$  are selected for the analysis. Further cuts are based on the track multiplicity in Station C ( $N_{\text{track}} > 4$ ) and the number of hit pairs in Station B ( $N^B > 0$ ). It is evident that two different classes of events exist. The background contribution is dominant in one station data and is characterized by small bundle sizes ( $< 100$  cm). The peak maximum of background events is diminished by a factor of  $\sim 100$  if a coincidence hit in Station B is required. The EAS events are characterized by  $\langle R \rangle$ -values corresponding to the expectation from CORSIKA-QGSJET01 [4] simulation and many also extend to Station B, thus passing the coincidence criterion  $N^B > 0$ .

The track multiplicity distributions in Station C are shown in figure 3 for two cases. For one-station analysis, the EAS can be selected by  $P < 1.375 \cdot (\langle R \rangle - 48 \text{ cm})$ . For two-station analysis, a cut  $\langle R \rangle > 70$  cm is used. The number of events decreases if the coincidence of two stations is required. This is due to the fact that not all EAS, which yield multiple muon tracks in Station C, yield coincidence hits also in Station B. The highest-multiplicity events pass both of the cuts, as is expected due to the correlation of local muon densities in the shower. The data are compared with a CORSIKA simulation for the muon multiplicities expected in Station C. The spectrum is pure proton with spectral index  $\gamma = -2.7$  below  $E = 4 \cdot 10^{15}$  eV and  $\gamma = -3.1$  above. The simulation is in general agreement with the data further proving the EAS extraction as valid.



**Figure 3.** Preliminary muon multiplicity distribution in Station C for 44 days of data taking. Extraction with one-station method (open circles) and extraction with two-station method (open squares). The symbols overlap for the highest multiplicities. A CORSIKA simulation expectation normalized appropriately is drawn as a solid red line. Different primary energies contribute up to different multiplicities. The energy labels denote the approximative energies with the largest yields to the multiplicity.

#### 4. Discussion

The background events are interpreted as single-muon-induced particle showers. Such events may exhibit a multitude of hits around a straight trajectory, which may cause false interpretations of multiple parallel tracks. The average number of hits contributing to the fitted track is lower in the background events than in the EAS. The multiplicity distribution of background events is close to exponential indicating a stochastic origin. These events can be discarded with the methods presented, but are also to be separately studied in more detail.

The comparison shown in figure 3 demonstrates the EAS selection method. More systematical effects related to the optimal tracking parameters and multitracking efficiencies, both on the simulation and reconstruction, must be investigated before proceeding to composition analysis. Therefore figure 3 is not to be interpreted as a result of such an analysis.

#### 5. Conclusion

The EAS selection in the EMMA underground array can be approached by two different means. Events recorded by one array station can be classified according to the bundle size and reconstruction purity, which disentangles the Extended Air Showers and the single-muon-induced background. A requirement of a coincidence between two detector stations diminishes the background. In upcoming data taking with multiple stations, the use of these methods will result in background-free EAS selection.

#### Acknowledgments

The support from the Magnus Ehrnrooth Foundation, the Vilho, Yrjö and Kalle Väisälä Foundation, the Finnish Cultural Foundation, and the Jenny and Antti Wihuri Foundation is gratefully acknowledged. The work is funded by the European Union Regional Development Fund and it has also been supported by the Academy of Finland (projects 108991, 7108875 and 7106570).

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