Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B (Proc. Suppl.) 175–176 (2008) 307–310
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
www.elsevierphysics.com

EMMA – a new underground cosmic-ray experiment

T. Enqvist[a]*, J. Joutsenvaara[a], T. Jämsén[b], P. Keränen[c], P. Kuusiniemi[a], M. Lehtola[d], A. Mattila[d], J. Narkilahti[d], J. Peltoniemi[d], A. Pennanen[a], T. Räihä[d], J. Sarkamo[d], C. Shen[a], W. Trzaska[e], I. Usoskin[b], M. Vaittinen[d], and Z. Zhang[a]

[a]Centre for Underground Physics at Pyhäsalmi (CUPP), University of Oulu, P.O. Box 22, FI-86801 Pyhäsalmi, Finland

[b]Sodankylä Geophysical Observatory (SGO), University of Oulu, Oulu, Finland

[c]Radiation and Nuclear Safety Authority – STUK, Helsinki, Finland

[d]Centre for Underground Physics at Pyhäsalmi (CUPP), University of Oulu, Oulu, Finland

[e]Department of Physics, University of Jyväskylä (JYFL), Jyväskylä, Finland

A new cosmic-ray experiment is under construction in the Pyhäsalmi mine, Finland. It aims to study the (mass) composition of cosmic rays at and above the *knee* region. The array, called EMMA, will cover approximately 150 m^2 of detector area at a depth of 85 metres ($\sim$240 mwe). It is capable of measuring the multiplicity and the lateral distribution of underground muons and the arrival direction of the air shower. The full-size array is expected to be ready by the end of 2007. A partial-size array (one third of the full size) is planned to record data already at the first quarter of 2007. It is also expected that the array is capable of measuring such high-multiplicity muon bundles that were observed at the cosmic-ray experiments at the LEP detectors.

1. INTRODUCTION

The origin of the small change in the cosmic-ray energy spectrum at 10^{15} – 10^{16} eV, i.e. the knee, has been one of the main questions of cosmic-ray physics, and has been discussed for decades. Some new experimental efforts have been devoted to the study of cosmic rays in recent years. These experiments are based, for example, on multi-parameter measurements of extensive air-showers, on shower maximum measurement by Čerenkov or fluorescence detectors and on underground multimuon measurements (see, for example, Ref. [1] and references therein). Their conclusions, however, have been diverse, implying the need for further studies, especially using different approaches.

EMMA (Experiment with MultiMuon Array) uses a different experimental approach. It is not the first underground cosmic-ray experiment (see, for example, Refs. [2–6]), but it differs significantly from previous underground experiments with its ability to measure the lateral distribution function of high-energy muons. In EMMA the composition analysis is based on the lateral distribution of high-energy muons and their multiplicity. The muons detected by EMMA are generated in the upper part of the air shower close to the primary interaction.

2. EXPERIMENTAL DETAILS

The present experiment will be carried out at a depth of 85 metres in the Pyhäsalmi mine (owned by the Inmet Mining Corporation Ltd., Canada) situated in the central Finland.

The detector array is placed at a depth of 85 metres (corresponding 240 m.w.e) which provides a threshold energy of muons of approximately 50 GeV. The rock overburden filters out all other charged particles of the air shower except the

---

*Corresponding author.
Email address: timo.enqvist@oulu.fi (T. Enqvist)

0920-5632/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.nuclphysbps.2007.11.018

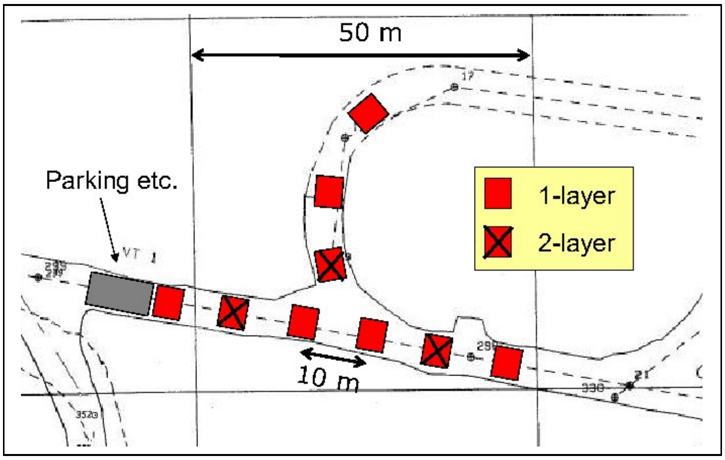

Figure 1. Schematic layout of the EMMA array in the underground site at 85 metres. The array consists of nine detector units each having an area of about 15 m^2. The horizontal and vertical dimensions are approximately 60 and 35 metres, respectively. The three crossed units occupy detectors in two layers for the shower direction measurement.

high-energy muons. A schematic layout of the array is shown in Fig. 1, where each of the nine units have an area of approximately 15 m^2.

The EMMA detector array consists of drift chambers previously used in the LEP–DELPHI experiments at CERN [7]. The total detector area of the setup is approximately 150 m^2 and it is able to measure the arrival direction of the air shower (by tracking), the muon multiplicity and their lateral distribution.

Most of the drift chambers have an active volume of $365\times20\times1.6$ cm^3. A plank consists of seven chambers (partly overlapped) having an area of approximately 3 m^2 and they operate in the proportional mode, with Ar:CO_2 (92:8) nonflammable gas mixture. Due to safety issues, the gas mixture does not contain formerly used CH_4. Each drift chamber can provide up to three signals, one anode signal and two delay-line signals (near and far), which are used for position information.

The acceptance of the array, assuming an area where the shower axis can be determined with an accuracy better than 6 metres, was estimated to be approximately 300 $m^2\cdot sr$ for 4-PeV proton-initiated shower.

3. LOCATING SHOWER AXIS

The reconstruction accuracy of the shower axis depends on the hit position. With the current detector layout (see Fig. 1) the average accuracy of better than 6 metres can be achieved in a large collection area. This is illustrated in Fig. 2, where 300 proton-initiated showers at 4 PeV have been dropped into each cluster. In this example, the collection area is approximately 300 m^2 in which the shower-axis reconstruction is on average better than 6 metres.

The lateral distribution function of high-energy muons was parametrised as

$$\rho(r) = \frac{N_\mu}{2\pi \cdot 0.11 \cdot R_0^2} \cdot \left(\frac{r}{R_0}\right)^{-0.4} \cdot \left(1+\frac{r}{R_0}\right)^{-5} \qquad (1)$$

using CORSIKA (QGSJET01c) [8,9] simulations. In Eq. (1), r is the distance from the shower axis, N_μ is the total number of muons, and R_0 is related to the gradient of the lateral distribution function. At the knee energies various air-shower models result in approximately similar shapes for

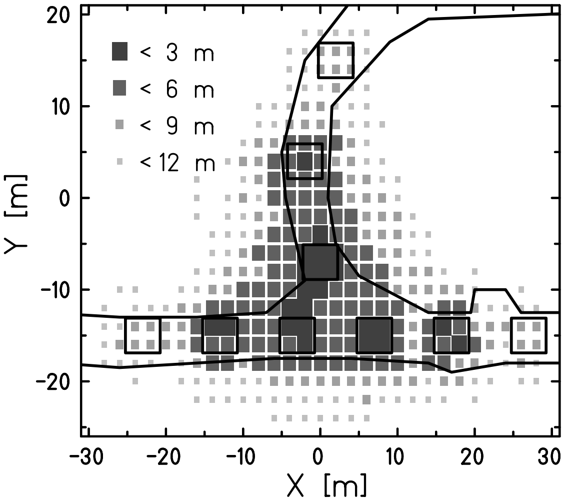

Figure 2. The accuracy of the reconstructed shower axis is shown as a cluster plot for a 4-PeV proton shower. The symbols represent the average shower axis uncertainty. The area where the shower axis can be determined with an average accuracy better than 6 metres is approximately 300 m^2. Each cluster contains 300 showers.

the lateral distribution function.

In order to locate the shower axis, a two-dimensional fit routine employing Eq. (1) was developed. The density distribution of the hit coordinates of muons (bin size 1×1 m^2) is used as an input for the routine (together with the assumption of the shape). The output values of the fitting routine are the shower axis location, total number of muons in the shower (above the threshold energy), and parameter $\mathrm{R_0}$.

4. EXTRACTING COMPOSITION

The idea of extracting primary cosmic-ray mass composition is based on the fact that the lateral distribution of high-energy muons is sensitive to primary particles and their energies. The number of muons at the shower axis can be used as an indicator for the primary energy. The energy resolution of EMMA according to this preliminary analysis is somewhat moderate.

The composition reconstruction simulations have been performed with a realistic energy spectrum and various proton-iron fractions were assumed for. The energy interval of 0.8−20 PeV was selected and the spectral index of −2.7 was used. The shower axes were distributed uniformly in an area of 160 × 160 m^2. The simulated sample consisted of 2×10^6 showers.

The data for the composition reconstruction was selected by applying two cuts to the total data set. First, there needed to be more than ten hits in at least one detector unit. Second, the reconstructed shower axis was within a triangular area surrounding the three centermost units. By fitting Eq. (1) resulted parameter $\mathrm{R_0}$ and the value of the lateral distribution one metre from the shower axis (ρ_1). All showers were fitted and a two-dimensional distribution of $\mathrm{N}(\rho_1,\ \mathrm{R_0})$ was created. The response functions for monoenergetic showers $\mathrm{f_i^p}(\rho_1, \mathrm{R_0})$ and $\mathrm{f_i^{Fe}}(\rho_1, \mathrm{R_0})$ were created similarly.

To reconstruct the primary composition, a maximum likelihood analysis was carried out by minimising the error of

$$\mathrm{N}(\rho_1, \mathrm{R_0}) = \sum_{\mathrm{i}} (\mathrm{P_i} \times \mathrm{f_i^p} + \mathrm{Fe_i} \times \mathrm{f_i^{Fe}}), \qquad (2)$$

where the variables $\mathrm{P_i}$ and $\mathrm{Fe_i}$ describe the amount of each individual component in the data in the energy bin i. The outcome of the method is illustrated in Fig. 3.

5. HIGH MUON MULTIPLICITIES

In the cosmic-ray experiments at LEP (DELPHI, CosmoALEPH, and L3+C) [10,4,11] events with high muon multiplicities were observed. While the small and medium muon bundles seem to fit into the model predictions, the production of the high multiplicities (above 80 or so) is not yet clear. These cosmic-ray experiments at LEP were short in time, effective running times of only about a month or two each.

The LEP experiments were not able to extract information on the lateral distribution of high-energy muons, and thus not directly on the pri-

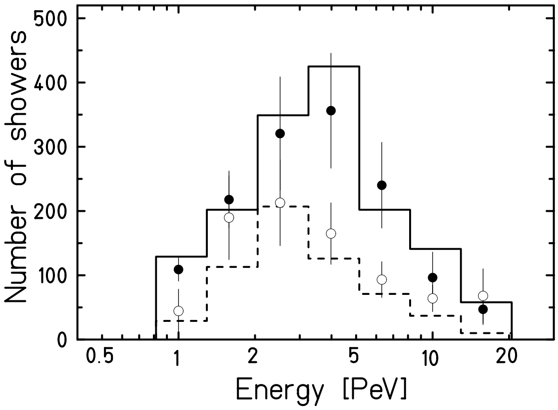

Figure 3. Reconstructed compositions for the initial condition of 80% proton (full symbols) and 20% iron (open symbols). Full histogram shows simulated proton composition and dashed histogram simulated iron composition.

mary particle producing the muon bundle.

EMMA is able to study the high-multiplicity events, already with a partial-size array. It is expected that EMMA can make a significant contribution to clear out the reason for the highest multiplicities. First, EMMA can measure the lateral distribution and thus obtain good information on the primary particle. In addition, this phenomena can now be studied systematically for several years.

6. SCHEDULE

The array is under construction. It is expected that first measurements could start with a partial-size array at the beginning of 2007. The construction work of the full array is expected to be ready by the end of 2007. The partial-size array is already large enough to observe the possible high muon-multiplicity events.

7. SUMMARY

A new underground cosmic-ray experiment EMMA is under construction and it is expected to start recording data in the full scale by the end of 2007. With a partial-size array the data recording can be started earlier. The analysis of simulated air showers shows that the primary cosmic-ray composition could be resolved at and above the knee energies. It is also expected that the anomaly of high-multiplicity muon bundles observed at CERN can be studied systematically with EMMA.

ACKNOWLEDGEMENTS

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

REFERENCES

1. Jörg R. Hörandel, astro-ph/0508014 (2005).
2. D. Cebula *et al.*, The Astrophysical Journal 358 (1990) 637.
3. S.M. Kasahara *et al.*, Physical Review D55 (1997) 5282.
4. V. Avati *et al.*, Astroparticle Physics 19 (2003) 513.
5. C. Grupen *et al.*, Nuclear Instruments and Methods A510 (2003) 190.
6. EAS-TOP Collaboration & MACRO Collaboration (M. Aglietta *et al.*), Astroparticle Physics 20 (2004) 641.
7. DELPHI Collaboration, Nuclear Instruments and Methods A303 (1991) 233.
8. D. Heck *et al.*, Report Forschungzentrum Karlsruhe 6019 (1998).
9. N.N. Kalmykov *et al.*, Nuclear Physics B (Proc. Suppl.) 52B (1997) 17.
10. Petr Travnicek, *Detection of high-energy muons in cosmic-ray showers*, Charles University, Prague, 2003, PhD. Thesis.
11. H.G.S. Wilkens, *Experimental study of high-energy muons from extensive air showers in the energy range 100 TeV to 10 PeV*, University of Nijmegen, 2003, PhD. Thesis.