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Underground multi-muon experiment EMMA

P. Kuusiniemi[1], L. Bezrukov[2], T. Enqvist[1], H. Fynbo[3], L. Inzhechik[2], P. Jones[4], J. Joutsenvaara[1], T. Kalliokoski[4], J. Karjalainen[1], K. Loo[1,4], B. Lubsandorzhiev[2], T. Monto[4], V. Petkov[2], T. Räihä[1], J. Sarkamo[1], M. Slupecki[4], W.H. Trzaska[4], and A. Virkajärvi[4]

[1]Oulu Southern Institute and Department of Physics, University of Oulu, Finland
[2]Institute of Nuclear Research, Russian Academy of Sciences, Moscow, Russia
[3]Department of Physics and Astronomy, University of Aarhus, Denmark
[4]Department of Physics, University of Jyväskylä, Finland

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Abstract. EMMA is a new experiment designed for cosmic-ray composition studies around the knee energy operating at the shallow depth underground in the Pyhäsalmi mine, Finland. The array has sufficient coverage and resolution to determine the multiplicity, the lateral density distribution and the arrival direction of high-energy muons on an event by event basis. Preliminary results on the muon multiplicity extracted using one detector station of the array are presented.

1 Introduction

Several underground experiments have investigated the cosmic-ray composition at the knee region (see, for example, Cebula, 1990; Kasara, 1997; Avati, 2003; Grupen, 2003; Aglietta, 2004). However, the results of these experiments are still inconclusive. In order to improve the situation the EMMA experiment (Experiment with MultiMuon Array) uses another approach: it measures the lateral density distribution of high-energy muons event-by-event.

EMMA is being built at a depth of 75 m (or 210 m.w.e) in the Pyhäsalmi mine, Finland. It is designed for cosmic-ray composition studies around the knee energy. The studies are carried out by measuring the multiplicity and the lateral spread of high-energy muons initiated by an air shower. In addition, the shower direction is extracted in order to estimate the muon energy cut-off. The rock overburden sets an average energy cut-off of approximately 50 GeV for vertical muons. Thus muons detected by EMMA are mostly generated in the upper part of the air shower close to the primary interaction.

According to CORSIKA simulation (Heck, 1998), in showers with energy in excess of 50 GeV, the muon lateral density distribution is sensitive to the energy and mass of the primary cosmic-ray particle. This is illustrated in Fig. 1 where the average muon density distributions of 1, 3 and 10 PeV proton and iron-initiated air showers are shown. In general the larger the muon energy cut-off (i.e. the deeper underground) the steeper are the tails (because more and more low-energy muons dominating in tails are stopped in the rock overburden) and the larger is the gap between proton and iron-initiated showers (because there are more muons available in iron-initiated showers). However, even a shallow depth filters out all particles but muons and provides better statistics (i.e. more muons) in the tails.

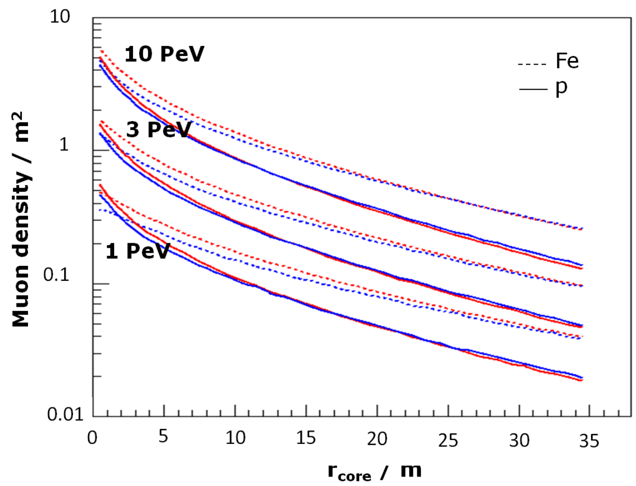

Fig. 1. Simulated lateral muon density distributions of high-energy muons ($E_\mu > 50$ GeV) of proton and iron-initiated air showers at 1, 3 and 10 PeV energies using CORSIKA+QGSJET 01 and CORSIKA+EPOS 1.99 indicated by red and blue lines, respectively.

Figure 1 reveals two interesting details important for EMMA: i) the primary energy translates to the muon density at the shower core and is somewhat independent on mass,

Correspondence to: P. Kuusiniemi
(pasi.kuusiniemi@oulu.fi)

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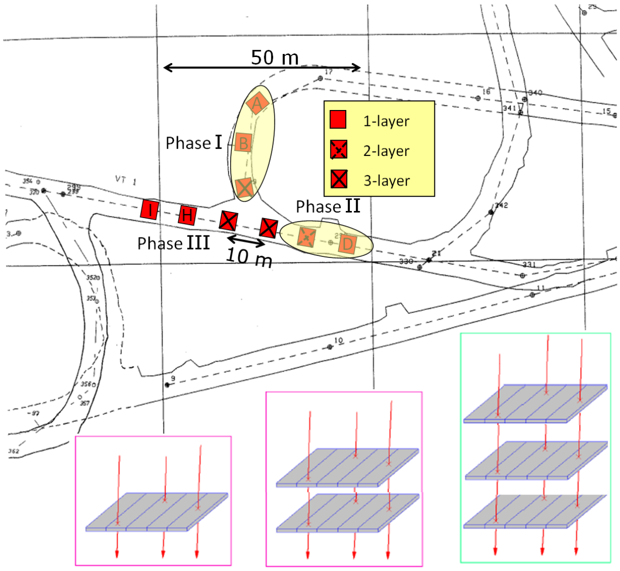

Fig. 2. Layout of EMMA. The shaded detector stations are currently installed. Phase I, II and III refer to the three branches of the array.

and ii) the tails of proton and iron-initiated showers are well separated. Furthermore, according to simulation event-by-event fluctuations ($\pm\sigma$) in the average number of muons (n) within 5 m from the shower core are rather high (σ/n $\sim$ 40% for proton and $\sim$ 20% for iron) but fluctuations predicted by different models seem rather similar (within $\sim$ 10%), and are taken into account in the composition analysis. Therefore one assumes that the muon density at the shower core and the muon density gradient can be used to estimate the energy and mass of primary cosmic rays, respectively.

2 Experimental set-up

EMMA has two unique features that sets it apart from previous experiments: i) while most previous ones are, or have been placed deep underground ($\sim$ 1 km), the shallow depth of EMMA is better suited to the knee energy event-by-event studies, and ii) EMMA is able to measure the muon lateral distribution for each shower.

The array consists of nine detector stations (see Fig. 2). Each station (out of which five, or those shaded in Fig. 2, are currently installed) has a detector area of approximately 15 m^2. EMMA employs two types of detectors, plastic scintillation detectors and drift chambers. The bulk area is covered with drift chambers that are former LEP-DELPHI MUBs (Aarnio, 1991), or planks. The planks are gas-filled at 1 atm with Ar(92%):CO_2(8%)-mixture. Each plank consists of seven position sensitive drift chambers (365$\times$20 cm^2, 20 mm thick) arranged in lengthwise half-overlapping groups of 3+4 (area of 2.9 m^2 each). The gas mixture is delivered from ground via an approximately 100 m pipeline through the rock. The latter is both safety and practical issue and allows us to avoid the gas transportation through the rather narrow mine caverns.

The position resolution of planks is in the order of $\pm$1 cm^2 and the muon detection efficiency is 90 - 95%. The position calibration is carried out in our surface laboratory employing atmospheric muons in a stack of 10 planks. In the stack every third plank, including the top and the botttom ones, are reference planks that were calibrated using a radioactive sodium source (^{22}Na). The position calibration (i.e. position vs. time registered by the TDC) is recorded using position vs. time tables instead of conventional polynomial fits to the time dependent positions. The advantage of the method is flexibility, i.e. it takes into account rapid changes in positions as a function of time because they are not smoothed out by a fit. As a result the position resolution of drift chambers is much better than 20 mm of FWHM. However, the method requires rather good statistics and as the calibration is carried out using atmospheric muons (which have rather constant yield) the time required for one calibration set of six planks is approximately six weeks.

While outermost detector stations, extending up to 30 m from the central one, host only one layer of planks (five planks placed side by side) the three central ones (marked with a cross in Fig. 2) have three layers of detectors with a vertical distances of approximately 1.1 m. These enable muon tracking for which, using the above given position resolutions and vertical distances, the angular resolution is better than one degree for single muons. The latter is important in order to estimate the muon energy cut-off and thus losses in the number of muons for each air-shower.

Despite the good position resolution of drift chambers their multi-muon detection efficiency is limited to a few muons within the chamber area because of pile-up signals due to after-pulses and multi-muon events. Thus high muon multiplicities at the shower centre may result in detector saturation. In order to overcome this limitation EMMA employs another set of detectors placed underneath the bottom layer of planks in the central stations (i.e. a fourth detector layer). These are plastic scintillation detectors equipped with WLS fibre and Geiger-mode APDs (Avalanche Photo Diodes) (Akhrameev, 2009) used in an underground cosmic-ray experiment for the first time. These state-of-the-art detectors (or SC16s) consist of 4$\times$4 individual small-size (12$\times$12$\times$3 cm^3) pixels having an active area of 0.5$\times$0.5 m^2. The total number of SC16s is 96 which translates to 24 m^2 or 1536 individual pixels providing EMMA with a large capacity of muon detection power, particularly for muon bundles with high muon multiplicities.

Parallel to the software development the scintillation detectors are checked (pixel by pixel) before placing them underground. Yet another task is the repair and calibration of another 30 planks which with the gas-filled detectors is often time-consuming.

3 Muon tracking

The rock overburden above EMMA is taken into account using GEANT4 (Agostinelli, 2003) simulations together with rock data provided by the mine. In addition the shower direction is obviously needed. This is carried out using tracking in the three tracking stations. Remarkably even after passing through the rock overburden muons are parallel within approximately one degree. The latter is an important result while reconstructing the muons tracks on the basis of muons hits detected by each detector layer.

The track reconstruction procedure is performed in two phases, first to find an initial guess for the shower arrival direction, and second to search for the most optimal tracks. As illustrated in Fig. 1 the number of muons is decreasing rapidly as a function of the distance from the core and as shown in Fig. 2 the distance between the tracking stations is approximately 10 m (and one station with two detector layers is even further away from the central ones). Thus the number of muon hits in at least one tracking station always remains reasonably small and one is able to use a 'check-all-possibilities' technique for the initial guess.

A candidate for the shower arrival direction is the one that has the largest number of parallel three-layer tracks and the most optimal tracks are searched for with respect to the reconstructed shower arrival direction. The judgements are based on their goodness-of-fit values and the final shower arrival direction is extracted using average angles. Performing the track reconstruction independently with all tracking stations and combining the results a reliable reconstruction for the shower arrival direction can be achieved. Furthermore, time and hit information from the scintillation detectors will provide an initial estimate for the shower arrival direction and will further improve the track reconstruction.

Because the tracking procedure is rather complex we have developed an event visualisation program using OpenGL and Root's TEve classes. The program can be used for both experimental and simulated data. The event information can be browsed via pop-ups, by summary tables and histograms. As an example Fig. 3 shows an event with 32 tracks.

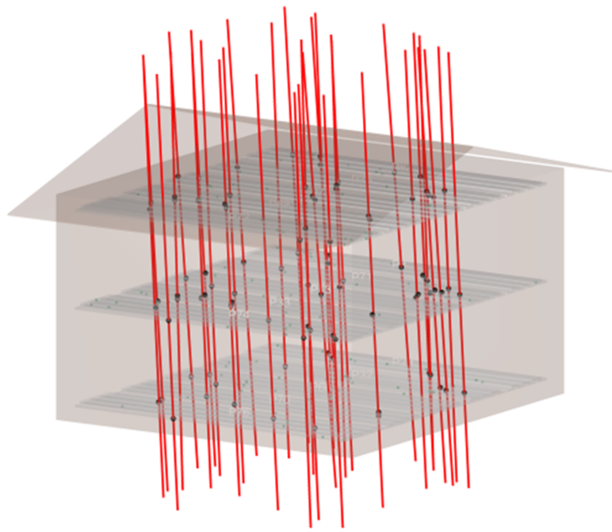

Fig. 3. A shower with 32 reconstructed tracks. The detector area in the tracking station is $3.65 \times 4.10\,\mathrm{m}^2$ and the gap between the two detector levels is approximately 1.1 m each.

4 Background discrimination - an example

The data recording in the first tracking station started in the beginning of 2010. These data are used, among others, for software development which particularly in case of tracking is essential as the data are complex and difficult to simulate to a full extent.

Because of inaccurate shower axis determination EMMA has its limitations for the composition study before Phase III is completed. However, there are still interesting topics available even for Phase I. One is the excess of very high-multiplicity muon bundles ($N_\mu \gtrsim 80$) indicated by the cosmic-ray experiments at LEP (DELPHI, CosmoALEPH and L3+C, see for example Abdullah, 2007), which fit poorly into the model predictions.

The data analysis in EMMA is carried out using both measured muon multiplicity data (i.e. the number of muons together with their positions in each detector station) and air-shower models. These data are thus interpreted in the framework of cosmic-ray physics (including, for example, interaction models) in order to extract the light (proton) and heavy (iron) component of the cosmic-ray composition around the knee energy.

The present data set consists of approximately two months recorded during spring 2010. These data are analysed in terms of background rejection development using solely close to vertical events ($\theta < 26°$). The recorded high-multiplicity events can be classified on the basis of their source.

For such a classification we use two variables, i) bundle size $\langle R \rangle = \Sigma_i^{N_{\mathrm{TRACK}}} r_i / N_{\mathrm{TRACK}}$ where r_i is the distance of a track to the mass centre of all the tracks in an event, and ii) event 'purity' i.e. the ratio between the number of hits and the number of tracks $N_{\mathrm{HITS}}/N_{\mathrm{TRACK}}$. The bundle-size $\langle R \rangle$ depends on the tracking station dimensions and track distributions while the ratio $N_{\mathrm{HITS}}/N_{\mathrm{TRACK}}$ depends on the detector efficiencies and muon induced electromagnetic sub-showers within the detector area.

The classification of events according to their size and purity (see Fig. 4) reveals two distinct classes of events. The peak with maximum at $\langle R \rangle \sim 300$ mm is interpreted as background events which are assumed to result from electromagnetic showers accompanying single muons. These events are thus characterized by large hit-to-track ratios and narrow hit

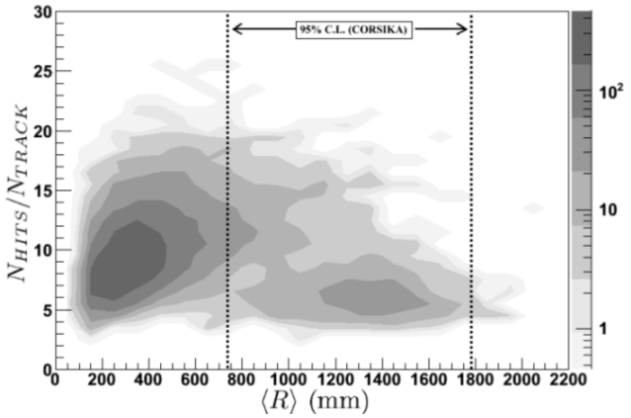

Fig. 4. The recorded multi-track events for track multiplicities $N_{\mathrm{TRACK}} > 4$ displayed according to the bundle size and reconstruction purity ($\langle R \rangle$ vs. $N_{\mathrm{HITS}}/N_{\mathrm{TRACK}}$). The number of events is indicated by contrast and the dashed lines indicate the limits of CORSIKA-expectation (the region of 95% of air showers).

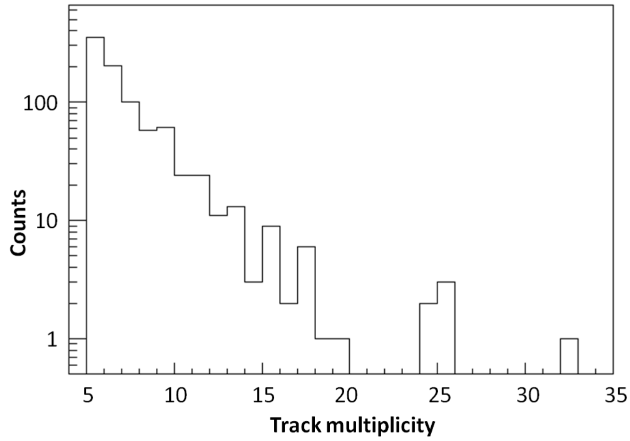

Fig. 5. Preliminary multiplicity distribution of close to vertical ($\theta < 26°$) muon bundles recorded within approximately two months.

and track distributions. The second peak with maximum at $\langle R \rangle \sim 1400$ mm is assumed to consists of the muon bundles associated with air showers. As expected on the basis of CORSIKA air-shower simulation predictions, in the bundle-like events the tracks are scattered around the detector area and hit-to-track ratios are small.

The above explained background discrimination method is a first step towards the analysis of multiplicity distributions. The preliminary multiplicity distribution of muon bundles measured in one detector station is shown in Fig. 5.

5 Conclusions

The new cosmic-ray experiment EMMA is under construction at the depth of 75 m (210 m.w.e.) in the Pyhäsalmi mine, Finland. Detector testing and calibration procedures are currently being carried out. Approximately a half of the detector stations have been installed and the first test measurements have been performed. The muon tracking software works well although more testing is still needed. The good position resolution of the drift chambers allow background rejection even in a single detector station. The situation will further improve as the rest of the detector stations will be completed.

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