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The EEE Project: a sparse array of telescopes for the measurement of cosmic ray muons

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Abstract: The Extreme Energy Events (EEE) Project is meant to be the most extensive experiment to detect secondary cosmic particles in Italy. To this aim, more than 50 telescopes have been built at CERN and installed in high schools distributed all over the Italian territory. Each EEE telescope comprises three large area Multigap Resistive Plate Chambers (MRPCs) and is capable of reconstructing the trajectories of the charged particles traversing it with a good angular resolution. The excellent performance of the EEE telescopes allows a large variety of studies, from measuring the local muon flux in a single telescope, to detecting extensive air showers producing time correlations in the same metropolitan area, to searching for large-scale correlations between showers detected in telescopes tens, hundreds or thousands of kilometers apart. In addition to its scientific goal, the EEE Project also has an educational and outreach objective, its aim being to motivate young people by involving them directly in a real experiment. High school students and teachers are involved in the construction, testing and start-up of the EEE telescope in their school, then in its maintenance and data-acquisition, and later in the analysis of the data. During the last couple of years a great boost has been given to the EEE Project through the organization of simultaneous and centralized data taking with the whole telescope array. The raw data from all telescopes are transferred to CNAF (Bologna), where they are reconstructed and stored. The data are currently being analyzed, looking at various topics: variation of the rate of cosmic muons with time, upward going muons, muon lifetime, search for anisotropies in the muon angular distribution and for time coincidences between stations. In this paper an overall description of the experiment is given, including the design, construction and performance of the telescopes. The operation of the whole array is also presented by showing the most recent physics results.

Keywords: Particle tracking detectors (Gaseous detectors); Large detector systems for particle and astroparticle physics; Large detector-systems performance; Resistive-plate chambers

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Contents

1 Introduction

Today most of the largest experiments devoted to cosmic ray physics are mainly oriented towards the detection and reconstruction of secondary showers initiated by high-energy primaries. They usually make use of a large number of detectors arranged to form a sparse array that covers a large area. In this respect new generations of cosmic ray experiments have arisen in the last years, trying to setup detection systems at schools, being usually distributed over large areas. Such networks generally do not have a large number of detection sites: each detection site usually consists of two or more detectors working in coincidence, but the separation distances between the sites could achieve several hundreds of kilometres. In such a way the detectors included in these arrays can provide local data on the local muon flux, can perform measurements of individual Extensive Air Showers (EAS) and finally can search for potential rare coincidences between two different air showers detected in sites placed hundreds of kilometres apart.

The Extreme Energy Events Project [1] can be included in the list of these large networks of cosmic ray detectors since it now consists of a huge array of detection stations which are placed in ~50 Italian schools. Its main peculiarity is the use of advanced detectors based on Multigap Resistive Plate Chambers (MRPCs), which allow to carry out sophisticated physics investigations. All these aspects make the EEE Project a unique tool to introduce high school students and teachers to research activities, as well as to carry out measurements of the cosmic ray radiation that produce scientific results. As a consequence, the operation of such network requires a strong and intense collaboration between high schools and research institutions.

The general organization of the Project is reported in section 2, together with a detailed description of the detector technology. Section 3 is focused on the performance of the MRPCs and of the EEE telescopes. Finally, the operation of the full array is presented in section 4 through the description of some examples of physics results.

2 The EEE Experiment

2.1 General description of the Project

The EEE Project was conceived in 2004 and is a collaboration of Centro Fermi [2], INFN [3] and CERN [4]. Its main goal is the study of cosmic ray muons by means of a sparse array of detectors distributed over all the Italian territory. Figure 1 shows an up-to-date map of the EEE detection sites (in red), together with the schools that are involved in the Project even without hosting the detector in their building (in blue). The result is a typical sparse array where each detection site, made of few close detectors placed in the same town, is far (hundreds of kilometers) from the others. Currently the largest distance between the EEE telescopes is about 1200 km (between CERN laboratories and Catania).

Figure 1. Map of the EEE network sites: the red points correspond to schools hosting a detector, the blue ones to schools participating in the EEE Project even without hosting a detector.

Except for a few sites, most of the detectors are installed in high schools: groups of students and teachers have built their detector at CERN and currently take care of its maintenance, operation and data acquisition. In the last three years more than 100 teachers and 500 students have been involved in the Project. The researchers coordinate and supervise the activities in each site, providing support during the construction, installation and use of the detectors. They also introduce students and teachers to the scientific research field through seminars, lectures and masterclasses organized during the school year.

2.2 Detector specifications

The EEE detector has been specifically designed in order to fulfil several requirements: large detection area, contained cost, long term operation, efficiency close to 100% and good time resolution (~100 ps). Moreover each detection station must provide the orientation of the incoming muons. The experimental setup consists of a telescope based on three layers of MRPC designed to be operated in "avalanche" mode, rather than in streamer mode, in order to reduce aging processes. The chambers consist of six gas gaps of 300 μm width, assuring higher efficiency and better time resolution than a traditional RPC. The cross-section of the device is shown in figure 2: the gas gaps are created by means of a sandwich of 5 internal glass plates spaced with a 300 μm diameter commercial fishing line. High voltage is applied on two additional external glass plates generating a uniform electric field between the glass electrodes. The chamber is fluxed with a mixture of SF_6 (2%) and Freon (98%), with a continuous flow of 3 l/h. DC/DC converters provide high voltage to the chambers, producing a voltage up to +10 kV (or −10 kV for the negative polarity) with an input voltage between 0 and 5 V. The DC/DC converters are mounted onto the MRPC, thus no high-voltage cables are needed. The signal produced by a charged particle traversing the chamber is induced on the pickup electrodes: 24 copper readout strips, each 2.5 cm wide and 180 cm long, are mounted on both sides of the stack of glass plates, lying longitudinally on two vetronite sheets with an area of $90 \times 180\,\mathrm{cm}^2$. This differential signal is used to reconstruct the hit position of the traversing particle: the coordinate along the long side on the chamber (X coordinate) is obtained by the time difference of the signal at the two ends of the strip fired, the coordinate along the short side (Y coordinate) is given by the position of fired strip itself. More details about the construction procedure of the EEE MRPCs can be found in [5, 6].

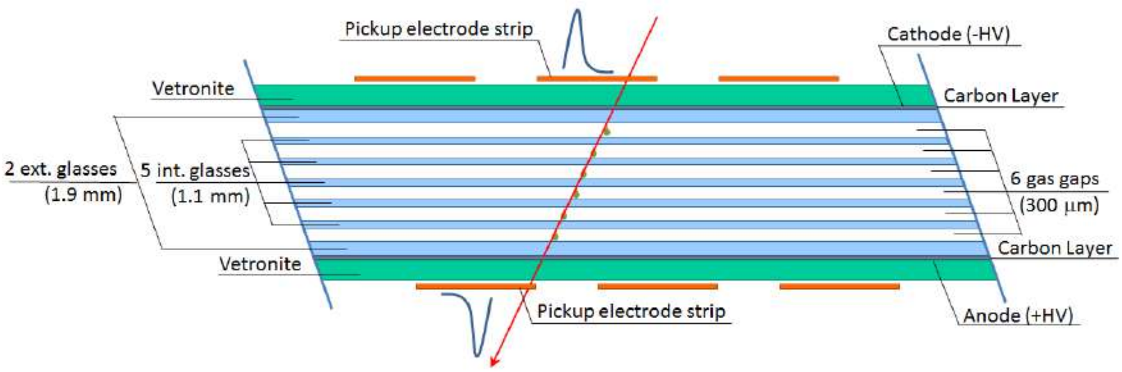

Figure 2. Cross-section of the EEE MRPCs (short side view).

The EEE telescope is made of 3 MRPCs, placed at a relative distance of 50 cm, resulting in a total telescope acceptance of $1.07\,\mathrm{m}^2\mathrm{sr}$. Each chamber is equipped on both short sides with a Front End (FE) electronics board based on the NINO asic [7]: the signals from the strips are amplified, discriminated and subsequently acquired by means of two high resolution commercial multi-hit TDCs. Each 24-channel FE board provides also the OR of the 24 inputs in order to produce a trigger signal given by the six-fold coincidence of the OR signals from both sides of all three MRPCs. The whole data acquisition system makes use of VME standards: the TDC modules and the trigger card are slotted into a VME crate that is connected to the DAQ computer by means of a CAEN USB-VME bridge module. The data acquisition software is based on LabVIEW and was developed at CERN for the EEE Project. Each station is also equipped with a Spectracom PCI Global Positioning System (GPS) card that is hosted inside the computer and read out by the DAQ program. The GPS unit, thanks to its high resolution, provides an absolute timing reference to remotely synchronize all the telescopes. Finally, data from Oregon Scientific weather stations are also integrated into the binary output files in order to correct the collected data for meteorological effects.

2.3 Current status of the Project

The EEE Project started with the construction of the first 7 pilot telescopes in 2005. After 10 years more than 50 telescopes have been built: most of them are fully working in Italian high schools, while two are installed at CERN and three at INFN sites in order to perform checks and develop new tools and solutions for the telescopes operation and data acquisition.

In order to achieve the highest operation efficiency, the data acquisition is performed through coordinated runs, during which the schools put effort into keeping their telescope running: after a three-week PILOT run at the end of 2014, the RUN1 was successfully organized in 2015, with about 35 telescopes participating in the data taking for a two-month period (March-April 2015) and an overall number of collected events around 5 billion; the second combined data taking, RUN2, started in October 2015 and lasted until end of May 2016, with 40 telescopes involved and 15 billion of events collected. The current run, RUN3, started at the end of October 2016 and will continue until June 2017. Up until now the EEE network of telescopes has collected more than 30 billion of cosmic tracks.

Because of the remarkable amount of data, the EEE Project joined the CNAF [8] cloud facility to create its own data collection centre. The CNAF cloud provides a flexible environment based on OpenStack and virtualization which allows to allocate on demand resources adapted to the need of the experiment and to collect data from the telescopes which are distributed in a wide territory. All schools have been connected to CNAF and they automatically transfer data, during coordinated runs, using a BitTorent technology [9].

Together with this storage service, the EEE experiment exploits the CPU resources of the CNAF centre by running an automatic analysis procedure for the reconstruction of the tracks. Once the runs are processed, many quality plots are made available and published on the web page devoted to the monitor [10]. Daily shifts have been organized to constantly monitor detector performance, both locally by groups of students specifically instructed, and remotely by an automated monitor procedure that produces a daily report describing the current status of the telescopes.

3 Performance of the EEE telescopes

The EEE MRPCs can be considered as the first large implementation of the MRPC technology. Their characteristics are similar to the ones built for the Time Of Flight (TOF) array of the ALICE Experiment at LHC. The performance of a single EEE MRPC was measured both at the CERN Proton Syncrotron facility [5] and at school during usual operation with cosmic rays [11, 12].

One of the main requirements taken into account during the design of EEE chambers is the need of high detection efficiency: since the acquisition trigger of a telescope is provided by the coincidence of 3 MRPCs, it follows that the detection efficiency can dramatically drop if the single chamber efficiency is not close to 100%. For this reason several studies were performed in order to optimize the gas mixture and the high voltage to be applied to the chambers. The first measurement of the EEE MRPC efficiency was performed at the PS facility with the help of two external scintillators that provided a trigger on the beam particles passing through the chamber under test. The efficiency turned out to be higher than 96% at a total applied voltage of 17 kV voltage. Also the students have performed an efficiency measurement of their telescope chambers at the end of RUN2: two chambers provided the trigger for cosmic rays passing through the third chamber that was under test. Special care was taken to avoid spurious coincidences. Some schools, with the help of researchers, have also repeated the measurement using traditional scintillators as trigger. All the results were compatible with what was obtained from the beam test. This measurement will be periodically replicated, to test the stability of the telescopes in terms of efficiency and to involve high-school teams in advanced experimental activities. The dependence of the efficiency on the applied HV has been reported in refs. [11–13].

A detailed study of the spatial resolution of the chambers was performed during the design and characterization of the first MRPCs, since the angular resolution of the telescope is a direct consequence of this characteristic. During the beam test at CERN PS the spatial resolution was measured on both coordinates of the chamber: on the short side, the resolution depends on the strip pitch (that is 3.2 cm) while on the long side it depends on the signal propagation along the strips. Accurate analyses showed that the EEE MRPCs exhibit a spatial resolution of ∼1 cm on both coordinates. More precisely the resolution slightly depends on the position along the strip, ranging from 0.7 to 1.2 cm along the X coordinate [5]. The measurement was replicated at school with cosmic rays by measuring the residuals on the middle chamber with respect to the direction reconstructed with the other 2 detection planes. As an example figure 3 shows a typical residual distribution along the Y coordinate (short side).

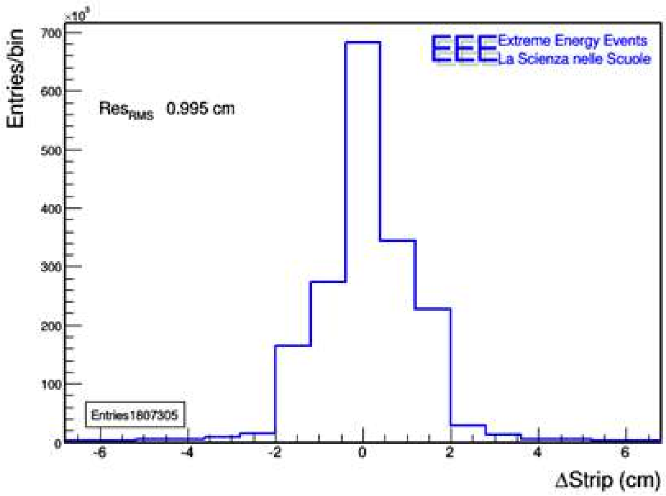

Figure 3. Typical distribution of the spatial residuals along the short side of the middle chamber of an EEE telescope. The RMS of the distribution (equal to 1.22 cm), provides a measure of the MRPC spatial resolution ($\mathrm{Res_{RMS}} = \sqrt{2/3} \times \mathrm{RMS} = 0.995$ cm).

Finally, another peculiarity of the EEE chambers is the optimal time resolution, which allows to perform measurements of the particles time of flight, considerably improving the quality of some data analyses. Relativistic cosmic muons need on average 3 ns to cross the telescope, from the top to the bottom chamber. The time resolution of the EEE chambers is good enough to allow TOF measurements, since the value measured during the beam test ranged from 65 to 80 ps, depending on the hit position along the strips [5]. This result has been obtained by correcting the data for time slewing due to the use of discriminators with fixed threshold. The time resolution of the chambers has also been measured at school: it turned out to be slightly higher (~200 ps) than the design specification but it is still consistent with what expected for cosmic rays. This result is also due to the use of TDC units with a worse time resolution (100 ps instead of 25 ps used during the beam test) and to the fact that no slewing correction was applied to the data [11, 12].

The global performance of the EEE telescopes is the result of the MRPCs characteristics already described. Considering a spatial resolution of 1 cm on both coordinates, it is possible to demonstrate, through geometrical simulations, that the direction of particles crossing the EEE telescopes is reconstructed with an error of 0.9°, that is a satisfactory result for the analyses carried out with the EEE telescopes.

Finally, the spatial and timing capabilities of the MRPCs affect the precision on the β measurement of the particles. The resolution on $1/\beta$ is of the order of 10% [11, 14].

4 Examples of physics studies

Most of the data collected during the coordinated runs have been analysed and many results have already been published. In this paper we will briefly focus on a few examples of analyses performed with our telescopes network. A more complete presentation of the results published by the collaboration can been found in refs. [14–20]. As discussed in the introduction, the EEE network is able to perform several kinds of physics analyses. First of all, each single telescope is able to monitor the local flux of the cosmic muons. The acceptance of the telescopes results in a trigger rate of the order of 30 Hz, which means that the EEE telescopes are sensitive to small flux variations (of the order of a few %) in 5 minutes of data taking. Together with periodic variations of the secondary cosmic rays flux, the network is able to detect the galactic cosmic-ray flux decreases (GCRDs) associated to solar phenomena such as Coronal Mass Emissions — the Forbush decreases, or solar flares, that usually take place over few hours. Figure 4 shows a typical Forbush decrease measured by one of the EEE telescopes placed in Catania (Sicily). The measured trend (decrease and recovery phase) is well in agreement with the cosmic neutron flux measured by a neutron monitor in OULU [21]. As expected, the muon component is less sensitive to such kind of events that are usually studied monitoring the flux of low energy neutrons.

The use of a network of telescopes allows to perform time and angular correlation studies between different detection sites. The relative distances of the EEE network telescopes range from a few hundreds of meters for clusters of 2, 3 and 4 telescopes in the same city, to more than 1000 km for the farthest stations. It means that telescopes placed in the same city can detect individual extensive air showers, whereas telescopes located hundreds of kilometers apart can, in principle, detect the coincidence between two different correlated air showers. The search of correlations between EASs is a challenging task, since no experimental evidence of such events has been observed so far. Moreover a huge statistics is necessary in order to reduce the statistical uncertainties. On the contrary, the detection of single EASs has been performed using couples

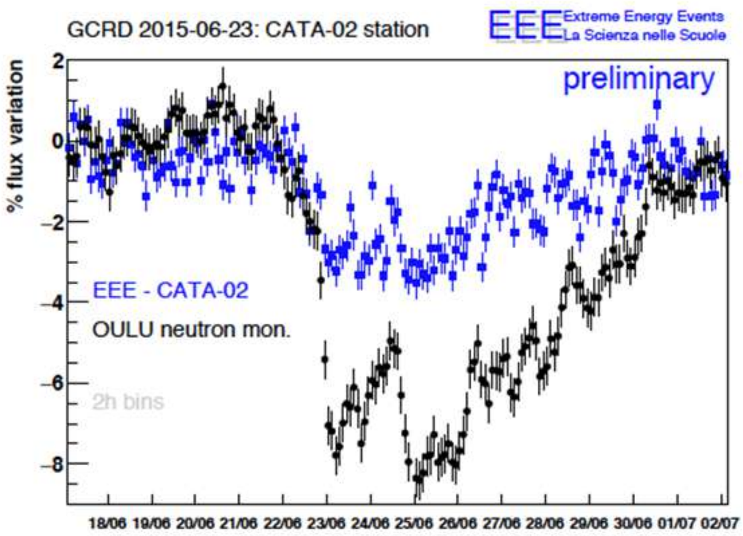

Figure 4. Typical Forbush decrease observed by one EEE telescope (squares), compared with OULU neutron monitor data measured in the same period (circles).

of telescopes placed in the same city, with a relative distance ranging from a few hundreds of meters to a few kilometers. Figure 5 shows, as an example, the time-difference spectrum obtained between two telescopes in Savona placed at a relative distance of about 1.2 km. The significance is $S/\sqrt{S+B} = 9.7$. To achieve the result shown, the time difference in figure 5 has been corrected, event by event, for the time delay between the two telescopes caused by the propagation of the wave front of the shower.

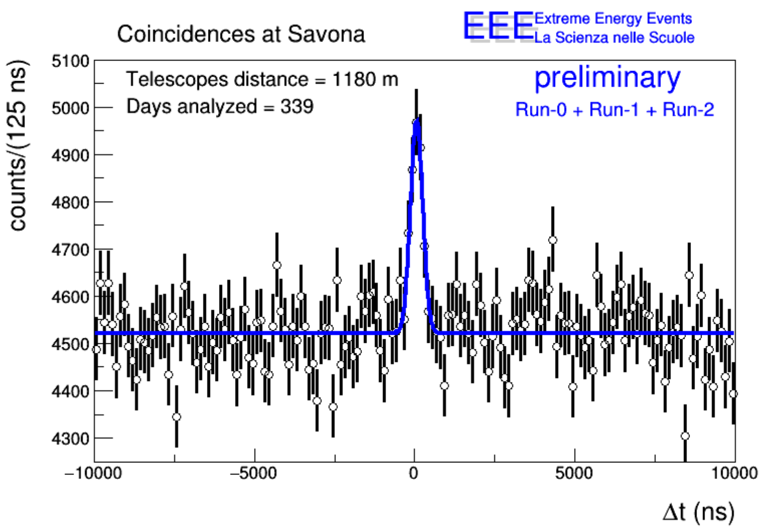

Figure 5. Typical time difference distribution measured between 2 EEE telescopes placed at a relative distance of 1.2 km in Savona.

The new statistics now available has opened up the possibility for new studies (such as the search for long-range correlations between EASs) and has improved the quality of the initial results

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already published.

5 Conclusions

The EEE Project successfully combines educational objective with scientific results. The network is continuously expanding since new detection stations will be added to the network in the next future. Every year new schools join the Project even without hosting a telescope: these schools can contribute to the data taking by collaborating with neighboring schools equipped with the telescopes; moreover they can also participate in the data analysis activities and take part to the national meetings between schools.

From a scientific point of view, in addition to the excellent results achieved so far, the increase of data expected after several years of full operation of the network will open a window on many other physics analyses.

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