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Regular Article

The EEE experiment project: status and first physics results

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This paper is dedicated to the memory of our friend and colleague Prof. Franco Romano, outstanding man and scientist, who recently passed away.

Abstract. The Extreme Energy Events Project is an experiment for the detection of Extensive Air Showers which exploits the Multigap Resistive Plate Chamber technology. At the moment 40 EEE muon telescopes, distributed all over the Italian territory, are taking data, allowing the relative analysis to produce the first interesting results, which are reported here. Moreover, this Project has a strong added value thanks to its effectiveness in terms of scientific communication, which derives from the peculiar way it was planned and carried on.

1 Introduction

Main goal of the Extreme Energy Events Project is studying the cosmic radiation, and in particular the one characterized by an energy greater than 10^{18} eV. This radiation lies in a still partially unexplored region of the cosmic rays spectrum, where problems related to its exact flux, composition and origin, make this investigation quite intriguing.

The EEE Project [1,2] was conceived in 2003 by professor Antonino Zichichi, and is presently carried out by a collaboration of several research institutes, like Centro Fermi, INFN, CERN and MIUR (the Italian Ministry of Education, University and Research). Essentially it makes use of the standard technique, consisting in detecting the muon component arriving to the ground of the extensive air showers generated by the energetic primaries when they enter the atmosphere. Due to the very high energy of the primaries, the corresponding showers are characterized by section areas of several km^2.

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Fig. 1. Distribution of the detection sites hosting EEE telescopes on the Italian territory. The numbers inside the stars indicate the presence of more than one EEE site in the same town. The total number of EEE sites is 40.

To reveal these particles, an array of many detection sites scattered all over the Italian territory (plus CERN) is foreseen. Each site hosts a muon tracking telescope made of three Multigap Resistive Plate Chambers (MRPCs) each, very similar, conceptually, to the chambers developed for the Time-Of-Flight system of the ALICE experiment at LHC [3,4].

The detection of an Extensive Air Shower (EAS, in the following) is operatively achieved by measuring the coincidences in time among events recorded at different sites of the EEE network. Therefore, the detectors used must combine a good tracking performance with an excellent time resolution, must be reliable on a long-term time line, easy to use and, possibly, cheap. All characteristics which are well met by the Multigap Resistive Plate chambers [5].

In addition to EAS of extreme energy, the EEE network will study also other interesting phenomena. For instance, a systematic study of the single muon flux and its variations, correlated with the relevant environmental parameters (local or astrophysical), is currently being carried on. Also an investigation of the feasibility of detecting upward going muons, exploiting the excellent time resolution that MRPCs provide, is presently starting and some preliminary results will be reported here.

Beyond its interesting scientific goals, the peculiarity of the EEE project lies in the fact that most of the activities related to the experiment have been —and still are— carried out by Italian high-school students and teachers, working in close contact with the scientists and technicians of the Universities, INFN and Centro Fermi. From the point of view of scientific communication and outreach activities, this is a very important added value to the Project.

In fact, the EEE detectors have been built at CERN by the teachers and students of the project, and the EEE sites presently located in Italian high schools —plus two at CERN, and one each at the Bologna and Catania INFN sections— are operated by people from these schools. The commissioning of the system was performed by mixed teams under the supervision of experts and researchers from scientific institutions. All this closely mixes in the very same activity the important didactic aspect deriving from taking direct part to a real scientific experiment, with the interest of performing a research in an advanced field of investigation [6].

2 Characteristics of the muon telescopes

An extensive description of the EEE Project telescopes has been already reported in several publications; for instance see, last in order of time, ref. [7]. Here just the most important info will be reported, for the sake of self-consistency.

The present network of the EEE Project is shown in fig. 1; as of today, it consists of 40 telescopes located at various high schools (or at two INFN sections, and CERN) distributed all across the Italian territory, with clusters of 2, 3 or 4 telescopes concentrated in some cities, and additional sites located more distant to increase the total surface covered.

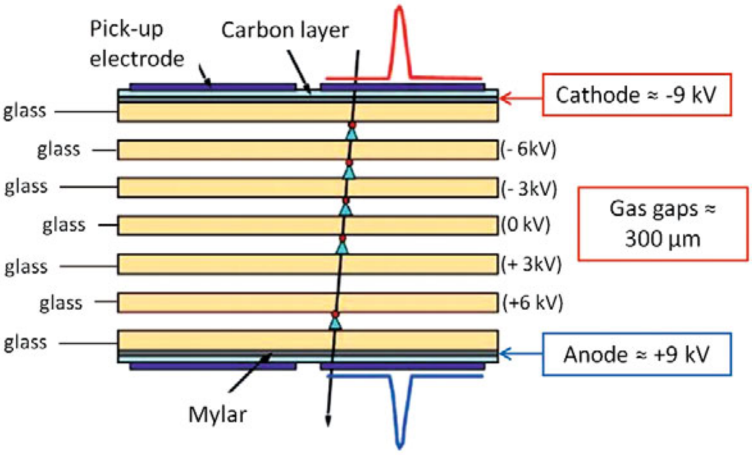


Fig. 2. Layout of a MRPC used for the EEE experiment.

Each EEE Project telescope is composed by three Multigap Resistive Plate Chambers (MRPCs), characterized by an active area of about 2 m^2. The MRPCs used, shown in fig. 2, have six gaps obtained by a stack of glass plate spaced 300 μm each by means of commercial fishing line, and characterized by a volume resistivity of about10^{13} Ωcm. The outer glass plates are coated with graphite painting, in order to be able to apply the high voltage and obtain the desired electric field in the gas gaps; when an ionizing particle passes through the gas, it creates a certain number of primary ion-electrons pairs, which are amplified in the usual avalanche process and finally induce a signal on the external readout strips. The gas filling the gaps is a mixture of $C_2H_2F_4/SF_6$ 98/2, while each MRPC is equipped with 24 copper strips 160 cm long, having a pitch of 3.2 cm.

The particle impact point is reconstructed by the hit strip in one direction and by the signal arrival time difference at the strip ends in the other direction. At the operating voltage of 18 kV, the measured MRPC efficiency is typically 95% and the time resolution is of the order of 100 ps, so that strip dimension, and time differences provide a spatial resolution of about 1 cm in both coordinates. The signals coming from the front-end cards are collected and processed when a triple coincidence of the MRPCs generates the trigger for the data acquisition. The absolute time of each event, necessary to spot coincidences between events recorded at different sites, is obtained by means of a Hytec GPS VME module.

2.1 Outreach activities

As already outlined in the Introduction, an important part of the EEE Project lies in its possibility to be a very effective method to communicate the meaning of the scientific research to a wide selected audience, summarized in its motto: “Bring Science to the heart of the young”. This was one of the reasons why it was decided to locate the EEE telescopes in high schools and to have students help “hands on” in the assembling, testing and monitoring of the detectors and in data taking and analysis.

The schools include both *Licei* (Italian secondary schools) specializing in classical or scientific studies and *Istituti Tecnici* (technical schools). The average number of students taking part to the EEE Project is around 30 per school, for a total of more than one thousand students each year.

After some introductory lessons by the school teachers on cosmic-ray physics and MRPC detectors, roughly ten students per school were selected to go to CERN —with 1 or 2 teachers— for a one-week stay to assemble the chambers, under the guidance of CERN and INFN researchers. This proved to be a very fruitful and exciting period for the students, usually at their very first visit to a big laboratory, during which they learn how to work in a team and live —even if only for a short time— the researcher life. At the end of the week they are taken to visit some of the LHC experiments, where they can see detectors very similar to the ones they just built and which are actually used in real experiments.

Once the chambers arrive at the schools, the students take part in the first tests: search of possible gas leaks, check the cable connections and perform, after explanation and with the help of the INFN people, the preliminary measurements of chamber efficiency.

Later on, during the data taking stage, the students are taught how to monitor the telescopes and they provide the daily checks which are mandatory to keep the system running. As some good data are available, the students learn how to treat and analyze them, using the very same analysis tool used in professional scientific research. Moreover, since younger students work in close contact with more experienced ones, the acquired skills are transmitted in the most natural way.

Almost all the schools, moreover, set up their own EEE Project web page, with links to Centro Fermi, CERN and INFN, where they store all the relevant info on about how the project develops at the different sites.

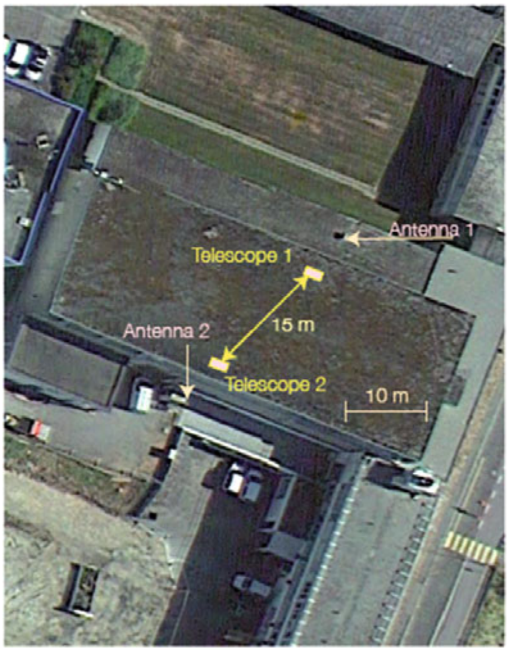


Fig. 3. Aerial view of the CERN hall where the two EEE telescopes are located.

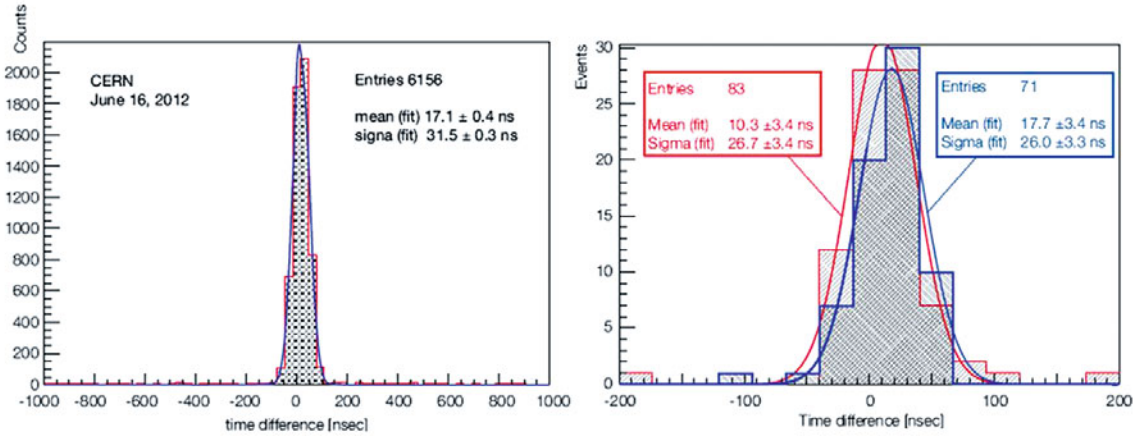


Fig. 4. Coincidence time spectra obtained from the two CERN telescopes without any angular cut (left) and applying the angular cut (right).

3 Some physics results

3.1 Coincidences

Results about the detection of coincidences among different telescopes have already been reported elsewhere. The first detection of EAS by means of the EEE network was performed at L'Aquila, where the two telescopes of the site were positioned at the closest distance among the telescopes of the network [8]. Later on, coincidences were detected also at the Cagliari site, where also two muon telescopes are less than a km far away from each other, and the relative preliminary results are shown in [7].

In fig. 3, we show an aerial view [9] of the hall at CERN where two EEE telescopes have been built and put into a data taking state. They are 15 m apart. The antennas for each telescope that are connected to the GPS cards in the two DAQ computers are located on opposite sides of the building, as shown in the figure.

Clearly, with the two telescopes located so close together, we expect to find a high flux of coincidence events. The data obtained during a single day of data taking are shown in fig. 4 and a coincidence peak is very well in evidence against the flat background due to the accidentals. The time spectrum of the coincidence peak has a sigma of 31 ns, which is coherent with the precision expected of the GPS system and the readout electronics used.

The average value of this coincidence peak depends on the angle of the incoming shower. In particular we projected the reconstructed tracks on the x-z plane of the local system of reference (where the x-axis is aligned with the N-S direction, while the z-axis is vertical) and measured the angles α_1 and α_2 of the two projected tracks with respect to z. For filling the right part of the same figure, we required the difference between the times measured by the two telescopes to be lower than $1\,\mu$s, and that $|\alpha_1 - \alpha_2| < 0.01$ radians. The blue histogram of the figure contains the events for which the average between α_1 and α_2 is positive, while the red one the tracks characterized by the same average being negative. This has the effect to separate the spectrum into two, and in fact a separation of 7 ns can be seen. The sigma of these two distributions is narrower than the total data sample.

Being this the main goal of the EEE Project scientific program, a systematic study on the number of coincidences detected at pairs of EEE telescopes is intensively investigated, by making use also of sophisticated Monte Carlo simulation programs (like CORSIKA or COSMOS) to compute the expected number of coincidences as a function of the distance between the two sites, their altitude, and so on. At the moment, it is evident from the data that the coincidence rate diminishes as the distance between the telescopes increases, as expected. From a certain distance on, a careful investigation on techniques for effectively rejecting the background of accidentals must be put in place.

3.2 Cosmic-ray flux variations

The EEE telescopes have been designed for a 24/7 operation. This characteristic makes the EEE array a powerful tool for monitoring the secondary cosmic-ray flux, that is usually affected by periodic and non-periodic variations. In fact, the high sensitivity of the EEE telescopes allows to detect small fluctuations of the local muon flux, due, for example, to meteorological effects (*i.e.* changes in the atmospheric pressure and temperature) or to daily variation effects related to solar phenomena.

Among the non-periodic intensity variations, rapid decreases of the galactic cosmic-ray flux due to solar activity (the so-called Forbush decreases) are the most common and the most interesting. They will be referred to in the following as GCR decreases. These events consist of an impressive transient change in the cosmic-ray intensity. They are characterized by a rapid (a few hours) intensity reduction, followed by a slow recovery in a few days time range. Such strong variations are probably related to solar flares and the associated geomagnetic disturbances [10]. A GCR decrease is a worldwide phenomenon which can be observed at all latitudes and longitudes. Monitoring of GCR decreases is usually done by means of neutron monitor detectors [11], since most of the intensity variation is associated to low-energy particles, whereas GeV muons are sensitive to more energetic primaries. However, especially in the case of large solar flares, these variations have been observed also by muon detectors [12], including the EEE telescopes [13].

As an example, here we describe the large GCR decrease of March 2012, as simultaneously observed by three detection sites of the EEE array. This GCR decrease is associated to one of the largest solar flares of solar cycle 24 happened on March 6th. More precisely, this flare was categorized as an X5.4, making it the second largest flare —after an X6.9 on August 9th, 2011— since the solar activity segued into a period of relatively low activity called solar minimum in early 2007. Figure 5 shows the flux of the secondary cosmics as a function of the time, for the neutron monitors (a) located in Oulu (65.05°N, 25.47°E) and Rome (41.90°N, 12.52°E) and for the EEE muon telescopes (b, c, d) placed, respectively, in Altamura (40.8°N, 16.6°E), Catania (37.5°N, 15.1°E) and Bologna (44.5°N, 11.3°E). The EEE telescopes used for this analysis are placed both at schools (Liceo Cagnazzi in Altamura, Liceo Galvani and Liceo Fermi in Bologna) and research centres (INFN Section of Bologna and Department of Physics in Catania). Since the neutron monitor in Rome is the site closest to the EEE telescopes, its data has been superimposed in plots b, c and d.

To compare data from the different telescopes, the vertical scale is expressed in terms of flux percentage variation with respect to a reference level, evaluated on the first 24 hours of the period under consideration (March 3rd to 13th). The data have been preventively corrected for variations due to meteorological effects.

The start of a GCR decrease is sometimes hard to be well defined and can vary with the position of the recording telescope. In fig. 5 the flux measured by the neutron detectors (upper plot) starts decreasing on March 7th, with a delay of nearly 1 day with respect to the solar flare time. Moreover the GCR decrease does not start from a constant level, but it is preceded by a slight intensity increase, as frequently observed in the past [14]. The magnitude of the decrease measured by the two neutron monitors is very different due to the geographical location of the two detectors: the vertical cutoff rigidity (*i.e.* the minimal energy a primary must have in order to produce secondary particles able to reach the Earth in that location) strongly affects the amplitude of the GCR decrease since low-energy primary cosmic rays are the leading actors in GCR decrease events. For this reason the decrease is approximately twice as large at the vertical cutoff rigidity of 0.78 GV in Oulu than at 6.32 GV in Rome. The flux variations measured by the three EEE telescopes are in good agreement with the neutron data: in all the sites the decrease starts and reaches its minimum almost in phase with the neutron monitors. The magnitude of the variation is less prominent than that observed for neutrons, since most of the intensity variation is associated to low-energy particles, whereas GeV muons are sensitive to more energetic primaries. The interpretation of the muon data is not trivial: small differences in the magnitude of the decrease or in its trend, between the different sites, can be imputed to the interplay of many factors, such as the geographical location (longitude and latitude) and specific working conditions of the experimental apparatus.

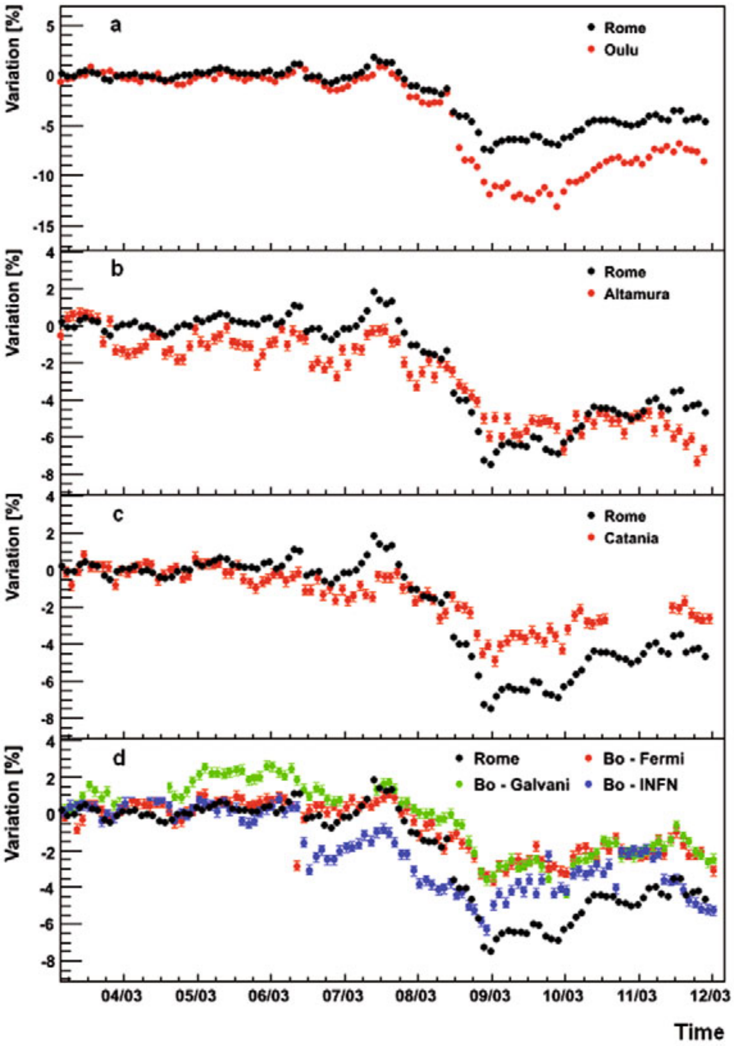


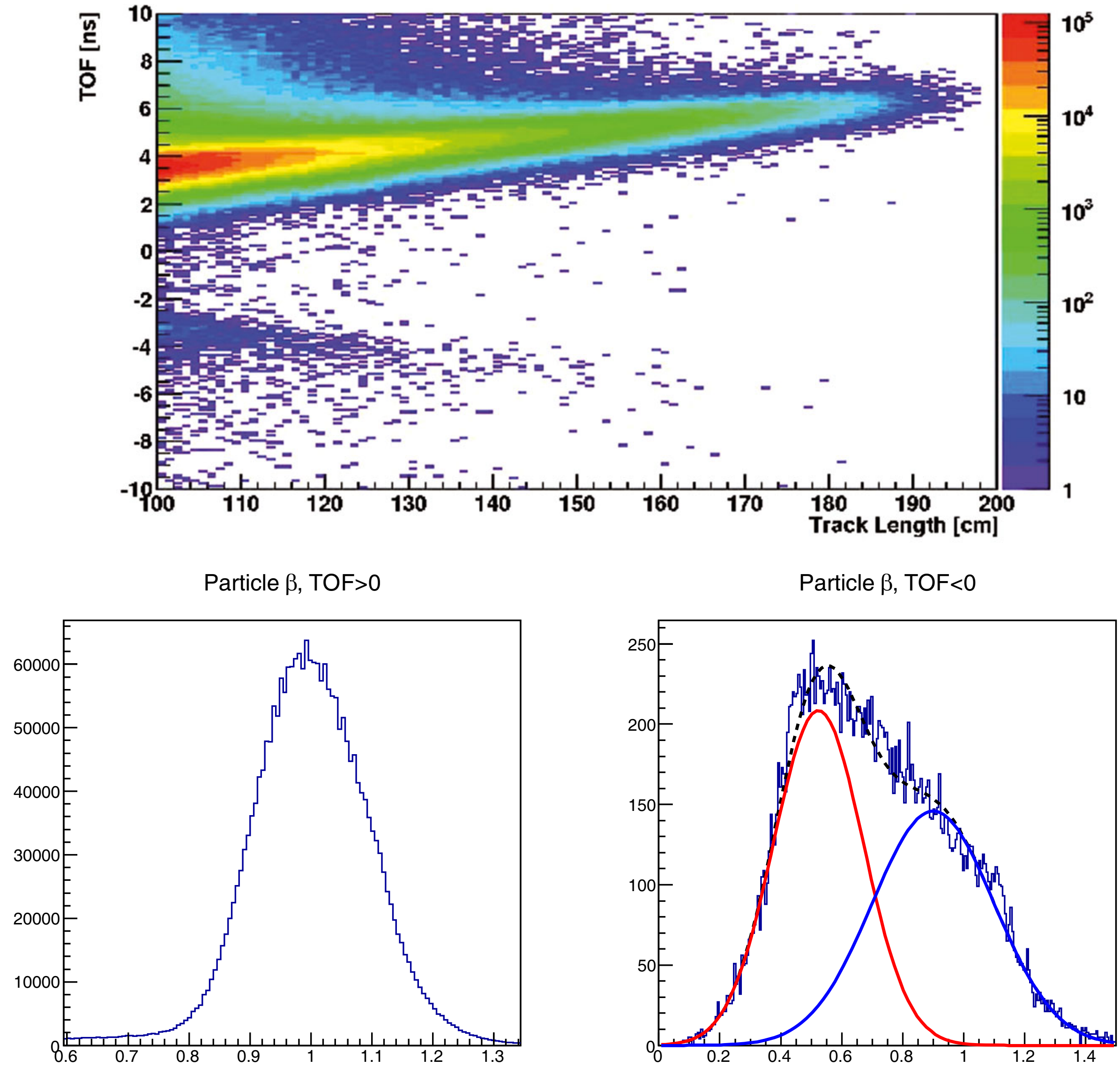
Fig. 5. The March 2012 GCR decrease, as observed by (a) the Oulu and Rome detectors of the Neutron Monitor Network and by (b) the Altamura, (c) Catania, and (d) Bologna EEE telescopes. For an easier comparison, the EEE measurements are superimposed to the Rome data.

The cutoff rigidity of the EEE sites ranges between 5 and 9 GV and the observed variation is much more similar to what measured by the closest neutron monitor in Rome. Moreover, the altitude of the detection site may affect the amplitude of the variation. More precisely, the magnitude of the GCR decrease is greater at higher altitudes (that is the case of Altamura at 420 m above sea level), and this effect goes on decreasing with increasing latitude [15].

Taking into account all these aspects, the data measured by the EEE telescopes are in good agreement with those measured by neutron monitors. Additional EEE sites have detected the same GCR decrease but the results will be discussed in detail in future works. Finally, the EEE telescopes are a powerful tool for the study of GCR decrease thanks to their capability to reconstruct the direction of the incoming muons. In principle, this feature allows to investigate the dependence of the GCR decrease effect upon the zenithal angle of the muons, which is correlated —to some extent— to the energy of cosmic-ray primaries.

3.3 Observation of upward charged particles

The study of the upward muon flux component is of interest both for cosmic-ray physics and astrophysics. The presence of the planet Earth on the path of traveling particles serves as a dumper for any particle species except for neutrinos, owing to their very low total cross section: the observation of an upward muon (coming from the ground) therefore could indicate a charged current interaction of a muon neutrino or antineutrino with the Earth and the production of a secondary muon close to the Earth crust.



Particle β, TOF>0

Particle β, TOF<0

Fig. 6. Top: TOF *vs.* length of the reconstructed track without cuts. Bottom, left: Velocity (normalized to the speed of light) spectrum for downward flux. Bottom, right: Velocity spectrum for upward flux; the solid lines are Gaussian contributions to the total flux; the dotted line is the sum of all contributions.

A flux of high-energy neutrinos is expected to be produced by the decay of high-energy hadrons, and therefore is strongly related to the flux of primary and secondary cosmic rays; moreover, high-energy neutrinos convert to high-energy muons traveling in directions close to the ones of the parent neutrinos. This information could be used to investigate possible sources, at least the most focused ones, like X-ray and γ-ray burst, some Active Galactic Nuclei, Supernova Remnants. In fact, signals for neutrino conversion in Earth are being studied or have already been obtained by several experiments, based mainly on Cherenkov light detection techniques, such as Super Kamiokande [16], Antares, Baikal, Amanda-IceCube and Nestor. However, the very low expected flux for such a signal with respect to the downward muon flux requires huge detection volumes, excellent time and angular resolutions, making these kind of astronomical studies a real challenge.

The EEE Project array is composed of tracking detectors, which are able to discriminate between upward and downward traveling particles by means of the Time-Of-Flight measurement. Each telescope is equipped with two TDC modules, the first receiving signals from the upper and lower chamber and the second from the middle chamber. The time information from the upper and lower chamber can be used to measure the TOF of the detected particle and to identify the traveling direction by its sign; the use of the same TDC for both the planes involved in the TOF measurement cancels out systematics coming from possible phase displacement among clocks of different TDCs.

We used data from the “Galileo Ferraris” (TORO-3) telescope in Turin in order to study the feasibility of an upward flux measurement. The EEE array in Turin is composed by four telescopes; three are placed at the corners of a triangle at an average relative distance of 1.1 km. The TORO-3 telescope, as for any EEE telescope, is made of three tracking planes, at a distance of 0.5 m: therefore the minimum path among the upper and lower plane is 1 m, and the actual path traveled by each detected particle between the upper an lower plane is determined by the hit coordinates on the two planes.

The TOF distribution, computed as outlined above, plotted against the length of the track is reported in the upper plot of fig. 6. This information has been used to obtain the velocity spectra for both upward and downward particle fluxes, shown in the lower plots of fig. 6. The criteria for track selection were based on the goodness of track reconstruction and on TOF values; the lower plots show only particle reconstructed with a hit position discrepancy with respect to the fitting track less than 3.2 cm and with TOF more than 3 ns (minimum physical value).

Two peaks can be clearly seen in the upper plot of fig. 6, one of which displaced at negative TOFs and revealing the presence of upward traveling particles. The peak in image at the left, showing the velocity distribution for downward particles, can be used in order to evaluate the telescope resolution for the β parameter; the Gaussian RMS of the distribution is 9.0×10^{-2} while its center is at $\beta = 1.001$. The plot on the right shows the velocity distribution for upward particles; at least two contributions are present: the position of the peaks and RMS are, respectively, 0.52 ± 0.15 and 0.9 ± 0.2. This measurement shows how EEE telescopes are able to distinguish the upward component of the flux and that the velocity resolution allows for the identification of relativistic and non-relativistic contributions.

The ratio between the upward and downward population is roughly 0.02, thus orders of magnitude above the expected signal for neutrino conversion; as expected, a strong background contribution coming from back-scattered muon is present and has to be precisely evaluated to perform further steps on the topic.

4 Conclusions

The Extreme Energy Events Project experiment is passing from its initial, building and commissioning phase, to the subsequent natural phase, characterized by the fact that almost all the sites are now continuously taking data.

The most difficult step, in fact, was putting in operation the telescopes, since this has involved a very relevant effort in terms of organization during the assembly and commissioning phases, chamber transportation, and, in general, coordination among the different components —scientists, technicians, students and teachers— of the Project.

From the hardware point of view, the detectors composing the telescopes have perfectly met the requirements of the experiment, in terms, for instance, of efficiency, spatial and time resolution. Many telescopes now have been taking data since several years without almost any interruption, which demonstrate the high reliability of this detector and of the associated system at the sites.

As a natural consequence, some of the studies planned in the design phase of the experiment have now enough collected data at disposal to be effectively carried out.

In this paper, in addition to results about the measured coincidences among the two CERN telescopes of the EEE Project, which have to be included in the general framework of the measurement of the flux of cosmic ray at the highest energy achievable, the observation of the March 2012 GCR decrease event is reported.

The data collected by the EEE Project experiment have a quality comparable to the one of Neutron Monitor Network, and provide additional information due to the fact that muons mantain their directionality. This could bring new insights on the GCR decreases related phenomena.

Finally, the possibility to detect upward going muons and separate them from the downward atmospheric muons has been investigated, giving rise to the first interesting results.

We acknowledge the NMDB database [11], founded under the European Union’s FP7 program (contract no. 213007) for providing data, and acknowledge individual monitors following the information given on the respective site information page. Nothing of what has been described here would have been possible without the hard work, passion, and dedication of all the students and teachers involved in the EEE Project. To them all goes the warm acknowledgment of the whole EEE scientific community.

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