Scientific and educational aspects of the EEE Project

P. La Rocca[ab], M. Abbrescia[ac], C. Avanzini[ad], L. Baldini[ad], R. Baldini Ferroli[ae], G. Batignani[ad], M. Battaglieri[af], S. Boi[ag], E. Bossini[ah], F. Carnesecchi[ai], C. Cicalò[ag], L. Cifarelli[ai], F. Coccetti[a], E. Coccia[aj], A. Corvaglia[ak], D. De Gruttola[al], S. De Pasquale[al], F. Fabbri[ae], L. Galante[am], P. Galeotti[am], M. Garbini[ai], G. Gemme[af], I. Gnesi[am], S. Grazzi[a], D. Hatzifotiadou[aio], Z. Liu[aop], G. Mandaglio[aq], G. Maron[r], M. N. Mazziotta[as], A. Mulliri[ag], R. Nania[ai], F. Noferini[ai], F. Nozzoli[at], F. Palmonari[ai], M. Panareo[ak], M. P. Panetta[ak], R. Paoletti[ah], C. Pellegrino[ai], L. Perasso[af], C. Pinto[ab], G. Piragino[am], S. Pisano[ae], F. Riggi[ab], G. Righini[a], C. Ripoli[al], M. Rizzi[ac], G. Sartorelli[ai], E. Scapparone[ai], M. Schioppa[au], A. Scribano[ad], M. Selvi[ai], G. Serri[ag], S Squarcia[af], M. Taiuti[af], G. Terreni[ad], A. Trifirò[aq], M. Trimarchi[aq], C. Vistoli[r], L. Votano[av], M. C. S. Williams[aio], A. Zichichi[aio], R. Zuyeuski[ao]

[a]Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Roma, Italy
[b]INFN and Dipartimento di Fisica e Astronomia "E.Majorana", Università di Catania, Catania, Italy
[c]INFN and Dipartimento Interateneo di Fisica, Università di Bari, Bari, Italy
[d]INFN and Dipartimento di Fisica, Università di Pisa, Pisa, Italy
[e]INFN, Laboratori Nazionali di Frascati, Frascati (RM), Italy
[f]INFN and Dipartimento di Fisica, Università di Genova, Genova, Italy
[g]INFN and Dipartimento di Fisica, Università di Cagliari, Cagliari, Italy
[h]INFN and Dipartimento di Fisica, Università di Siena, Siena, Italy
[i]INFN and Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[j]INFN and Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[k]INFN and Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[l]INFN and Dipartimento di Fisica, Università di Salerno, Salerno, Italy
[m]INFN and Dipartimento di Fisica, Università di Torino, Torino, Italy
[o]CERN, Geneva, Switzerland
[p]ICSC World laboratory, Geneva, Switzerland
[q]INFN Sezione di Catania and Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Università di Messina, Messina, Italy
[r]INFN-CNAF, Bologna, Italy
[s]INFN Sezione di Bari, Bari, Italy
[t]Trento Institute for Fundamental Physics and Applications, Trento, Italy
[u]INFN and Dipartimento di Fisica, Università della Calabria, Cosenza, Italy
[v]INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy

E-mail: `paola.larocca@ct.infn.it`

Abstract. The Extreme Energy Events (EEE) Project is an experiment aimed at the detection of secondary cosmic ray muons. It consists of a sparse array of about 60 telescopes, based on Multigap Resistive Plate Chambers (MRPCs), mostly distributed throughout the Italian territory, mainly in high schools locations, and at CERN. The telescopes are now operational and taking data since more than ten years with a high duty cycle and detection efficiency. The analysis activity is currently in progress and focused on several items, including the detailed study of the muon flux under different conditions, its connection with atmospheric and solar events, the detection of extensive air showers and the search for long distance correlations between different extensive air showers. In this paper an overall description of the experiment will be given, together with its educational fallout. The operation of the whole array is also discussed by showing the most recent results obtained from the analysis of the collected data.

1. Introduction

In the 100 years since the discovery of cosmic rays, a great deal has been learned about their composition, propagation and sources, mainly thanks to the development of different experimental techniques aimed at the detection of cosmic rays above and on the Earth's surface, underground and even underwater. In particular, the coincidence between surface detectors, arranged in arrays covering huge area (even several thousands km^2), allows the study of the main characteristics of extensive air showers, thus inferring about the properties of the primary cosmics that have generated the detected particle cascades. Besides the study of single EASs (Extensive Air Showers), in recent years the idea to investigate the existence of coincidences between independent EASs led to the development and construction of sparse arrays made of surface detectors displaced over very large area (even million km^2) but characterized by a loose spacing, typically exceeding the usual EAS size (a few km).

The Extreme Energy Events Project [1] is one of the most promising sparse array for the detection of cosmic radiation. Coordinated by the *Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi* - Rome [2], in close collaboration with MIUR, the Italian *Ministero dell'Università, dell'Istruzione e della Ricerca*, INFN [3] and CERN [4], the Project aim is to study cosmic rays by detecting and tracking the muon component of the extensive air showers produced by the interaction of high energy primary cosmic rays in the Earth atmosphere. In 2004 it was a "pilot" Project with just 7 detectors, in 2019 it is an experiment with 62 detectors, most of them installed in Italian High Schools except for two at CERN and four in INFN units, across an overall area of $\sim 3\times10^5$ km^2. Another goal of the EEE Project is to encourage scientific culture, through the involvement of a certain number of Italian high secondary schools in the construction, installation and maintenance of the detectors.

In this paper a general overview of the experiment will be given, including a description of the detectors, of the scientific and educational goals and of the main physics outcomes achieved so far.

2. The EEE detectors

The muons of cosmic ray showers arriving at the ground level are detected with very high accuracy by wide (82$\times$158 cm^2 of active area) Multigap Resistive Plate Chambers (MRPCs), quite similar to those used for the ALICE experiment Time Of Flight (TOF) detector: they were specifically designed for the EEE Project and are made of six gas gaps obtained interleaving two glass plates, coated with resistive paint (with a surface resistivity of about 5MΩ/square) and acting as electrodes, with five floating glasses [5]. The inner-glass spacing is assured through a weave made with fishing line, resulting in six narrow gaps (300 μm), continuously fluxed with a gas mixture of $C_2F_4H_2$ (98%) and SF_6 (2%). The MRPCs operate in avalanche mode with typical working HV = 18 kV supplied by safe EMCO-Q series DC/DC converters. Standalone LV power supply units, both commercial or custom engineered by the EEE Collaboration, provide the LV to the DC-DC converters.

On the outer surfaces a sheet of Mylar is stretched on a vetronite panel of equal area on whose external surface 24 copper strips are laid out (160 cm $\times$ 2.5 cm spaced by 7 mm), to collect

the signals induced by particles. These 24 copper strips (i.e. cathode and anode readout strips) are mounted on both sides of the stack of glass plates, giving rise to differential signals (sum of all gas avalanches in all the gaps), readout by front-end cards (FEA, 24 channels each, two per chamber plane) designed for MRPC operation and equipped with the NINO ASIC chip. This strip configuration is used to provide two-dimensional information when a particle crosses the chamber: one coordinate is given by the fired strip, while the second is obtained by the time difference of the arrival signals at the opposite edges in each strip, measured using two commercial multi-hit TDCs (CAEN V1190A/B, 100 ps resolution).
All the chambers are tested before the final installation by measuring their detection efficiency and streamer fraction curves [6]: all MRPCs show a similar behavior, with typical efficiencies better than 90% reached by 77% of the network. Most of the chambers were also characterized in terms of spatial and time resolution, showing an average precision of the order of 0.9 cm for the transverse coordinate and 1.4 cm for the longitudinal coordinate; the time resolution is of the order of 240 ps. These values were measured during the standard data taking with cosmic rays at school. Dedicated tests, performed under controlled conditions with beams at CERN in 2006, led to precise estimations of the spatial resolution (better than 1 cm on both position coordinates) and time resolution (70 ps).
In order to reconstruct the particle orientation, each detection system is made of 3 MRPCs arranged in a telescope configuration (Figure 1) and placed at a relative distance of 0.5 m. The trigger logic consists of a six-fold coincidence of the OR signals from the FEA cards, corresponding to a triple coincidence of both ends of the chambers. Due to the efficiency of the single chambers, the telescopes detect particles with an average efficiency of 80%.
Synchronization between telescopes is guaranteed by a GPS unit that provides the event time stamp with precision of the order of 40 ns. Data acquisition, monitoring and control are managed by a LabVIEW based program.

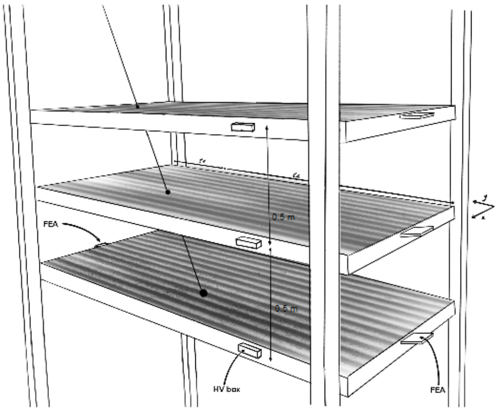

Figure 1. Left: Drawing of an EEE telescope, made of 3 MRPCs placed at 0.5 m on a support structure. Right: Picture of a typical installation in one of the school of the EEE network (ITIS Galileo Galilei in Arezzo).

Up to now, over 100 billion tracks have been collected during five data taking periods completed from 2014 to 2019, with up to 50 telescopes simultaneously working, for several months in each period. The data collected from the network are sent to the CNAF, the major INFN Computing Center located in Bologna, on a run-by-run basis - where they are stored, reconstructed and "quality monitored". The outputs - together with the raw data - are put on a web page which researchers and students can freely access to perform their own data monitoring and analysis [7].

3. Outreach mission and scientific goals

The main peculiarity of the EEE Project is to pursue scientific goals related to cosmic ray physics through the active involvement of several hundreds high school students and teachers, making them to participate directly to the construction and to the operation and monitoring of their school telescopes. During the last 10 years thousands of students participated to the Project and have been introduced to an advanced research work, experiencing all the phases of a true physics experiment: selected teams of students build the telescope chambers at the CERN laboratories under the supervision of researchers; they participate to the installation of the telescopes at school; they daily monitor the telescopes and the quality of the data, compiling a dedicated logbook; they attend monthly meeting where they can share their experience with researchers and students from other Italian regions; they have the possibility to learn about cosmic ray physics, detection techniques and related topics. All these activities can be summarized by the EEE motto *"Bring Science to the heart of the youngs"*.

In addition to this outreach mission, the scientific program of the EEE Project is related to the study of high energy cosmic rays: the topology of the array offers the possibility to study local cosmic rays variations (measured by means of single telescopes), to detect and study extensive air showers (thanks to the presence of several clusters of telescopes installed in the same city) and also the search for coincidence between air showers (looking for coincidences between far telescope clusters or telescopes).

Measurement of the local muon flux. With its 62 active sites and more than 13 years of data taking, the EEE network is currently the largest and long-living MRPC-based telescopes network. The telescopes cover a large area across the Italian and Switzerland territories, from Catania to CERN (with latitude from 37 to 46 degrees North) and from Lecce to CERN (with longitude from 6 to 18 degrees East). The extension of the EEE array, in terms of covered area and number of detection sites, together with its high duty cycle, offers the possibility to locally monitor the cosmic muon flux at different geographical locations. In such sense the EEE array is a unique observatory of the muon component of the cosmic radiation over the Italian territory. Such characteristic allows to study the effect of the solar activities on the muon flux measured at ground level [8, 9], to search for possible anisotropies in the arrival directions of the muons due to the properties of the local Earth magnetic field [10], to investigate shielding effects arising from the presence of buildings or natural structures surrounding the telescopes, and so on.

Detection of extensive air showers. Even if the average distance between the EEE telescopes largely exceeds the typical EAS size, the network also includes 10 detection sites where telescopes are grouped into local clusters of 2-4 stations , hence being able to detect extensive air showers. Several data samples have been already analized to measure the rate of coincidences for telescope clusters within few kilometers distance. The coincidence rate of each telescope cluster and the signal-to-noise ratio strongly depend on the relative distance between the telescopes in the cluster, and on the amount of spurious counting between them. In the most favorable conditions, i.e. at a distance of 15 m as for the two telescopes located in the CERN site, several thousand air showers per day are measured [11].

Search for coincidences between far telescopes. The possibility to observe time correlations between detectors separated by distances much larger than the extension of the highest-energy EAS is a subject of extreme interest since no clear experimental evidence of such events has been observed so far. The EEE system allows to perform such a search, thanks to its tracking capabilities, the DAQ stability and the huge amount of data now available. Several analysis approaches have been implemented, all leading to the evidence of few candidate coincidence events [12, 13, 14].

Even if some of these aspects are still under investigation or continuously updated, a selection of the most significant results produced by the EEE Project is reported in the next section.

4. Physics outcomes

Each telescope of the EEE network can monitor the muon rate during all day and over long periods, hence detecting cosmic rays flux variations that can be trivially due to changes of the atmospheric conditions (pressure and temperature), or to relevant events occurring on the solar heliosphere, such as flares and coronal mass ejections. Whereas the first kind of variations are well known and can be easily studied thanks to the atmospheric data collected by the weather stations installed close to each EEE telescope, the monitoring of variations related to solar activity is of interest for the understanding of phenomena that occur on the solar heliosphere, as well as on other observable stars. Several GCRDs (Galactic Cosmic Ray Decreases), also known as Forbush decreases, have been observed so far and compared to the results obtained with neutron monitors. An example of Forbush decrease observed by the EEE network is shown in Figure 2.

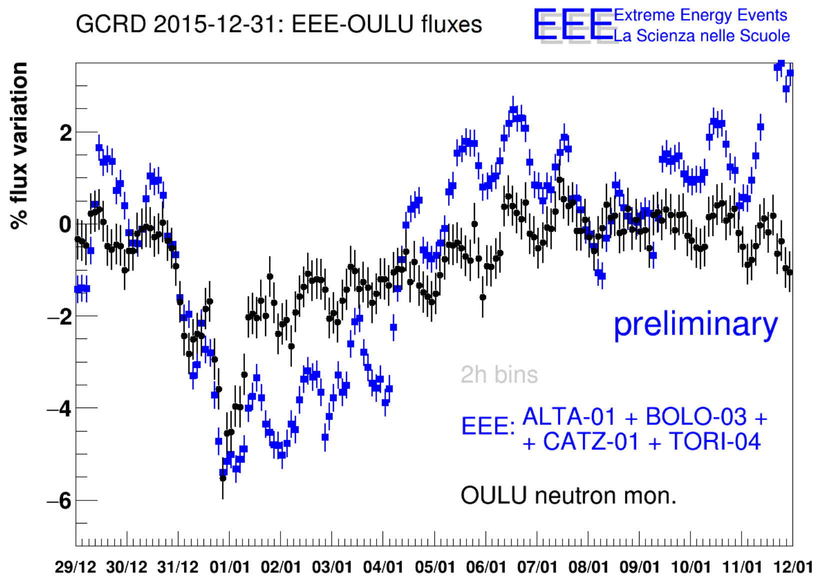

Figure 2. Variation of the cosmic-ray flux caused by a solar flare of class M1.8 occurred on December 31, 2015. The blue square points represent the percentage flux variation measured by 4 EEE telescopes, corrected for atmospheric pressure variation. In the same plot the corresponding neutron flux (black circles), as measured by the Oulu neutron station is also shown.

In addition to their stand-alone operation, that gives information about the local muon flux, all the telescopes are synchronized by a GPS unit that provides the event time stamp with a precision of the order of 40 ns. Thus, from the time and orientation correlations between two independent cosmic particles, the telescopes placed in the same city can detect individual EASs. As an example, Figure 3 shows the time differences - as measured using the GPS information - of events between two telescopes in Cagliari and in Savona, 520 meters and 1180 meters apart respectively.

The study of such short-distance time correlations not only gives information about some properties of the detected air showers, but can also provide a selective trigger for those analyses aiming at the investigation of rare events, such as the search for long-distance correlations between two different air showers. The possibility to observe cosmic rays time correlations between detectors separated by distances much larger than the typical extension of EASs has been long discussed over the years. A possible physical mechanism which could justify the existence of such events invokes the photodisintegration of a primary heavy nucleus in two lighter

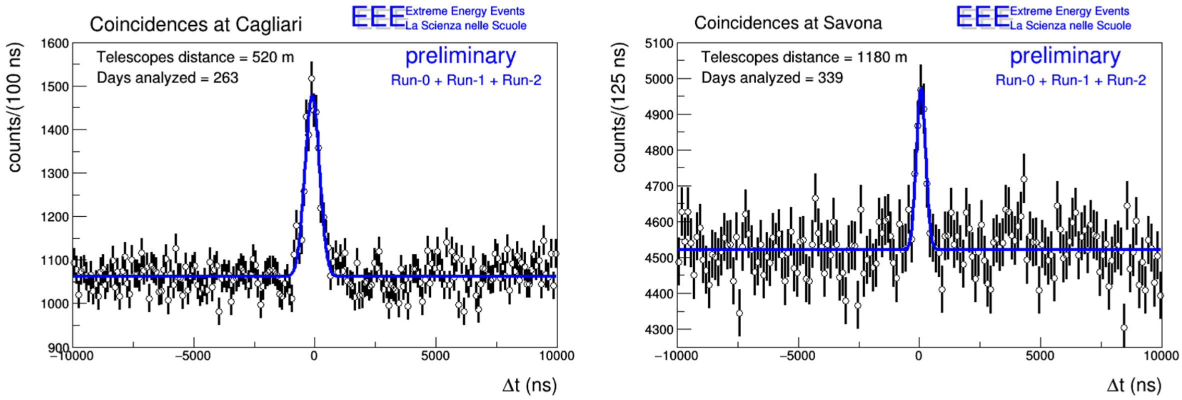

Figure 3. Time difference between events detected by two telescopes at a distance of 520 meters in Cagliari (left panel) and 1180 meters in Savona (right panel).

but highly energetic fragments by interaction with a solar photon (the so called GZ effect [15]). Being an extremely rare phenomenon, a huge statistics and optimized analysis strategies are necessary in order to reduce the statistical uncertainties and increase the signal-to-background ratio.
Since the correlation between independent telescopes due to their individual single rates is not selective enough, several analysis approaches have been implemented in order to handle the huge amount of spurious coincidence events between detectors and enhance the probability of observation of rare events. Hence custom offline triggers have been applied to select the events to be considered in the correlation analysis: a first attempt was done by analyzing EAS events detected by the clusters of telescopes. As a result, few candidate events which are characterized by small values of the time difference and in some cases also by a small angular difference were extracted from the analysis [13]. However most of the available data is consequently excluded by adopting this approach since only 10 detection sites of the EEE network host a cluster of telescopes. A different approach has been implemented, being based on the selection of multi-tracks events (i.e. events with 2 or more tracks of the same shower detected by a single telescope). A large sample of data, collected by the EEE network from 2013 to 2018, have been analyzed; by applying basic cuts on the quality of the tracks in each telescope ($\chi^2 < 10$), on their parallelism and multiplicity (scalar product with the seed track > 0.8 and $N_{tracks} > 3$), the number of coincidences between all the possible pairs of far telescopes (relative distance > 5 km) was estimated in time windows ranging from 10 μs to 1 s and compared with the number of accidental coincidences. Figure 4 shows the number of coincident events as a function of the time window for the selected multi-track events. In such conditions a small excess of events starts emerging over the accidental background for coincidence time windows smaller than 100 μs. The most significant excess corresponds to 40 coincident events, against 23.4 events due to the expected background. Additional checks are ongoing in order to investigate the characteristics of these possible candidate events (in terms of location of the sites involved, time of occurrence, parallelism of the two EASs, effect of the applied quality cuts) and to compare these results with the theoretical expectations.

5. Conclusions and outlook

The Extreme Energy Events network is fully operative, with more than 60 telescopes built by students and installed in high schools distributed over the whole of Italy. Thanks to its good performance and high duty cycle, more than 100 billion reconstructed tracks have been

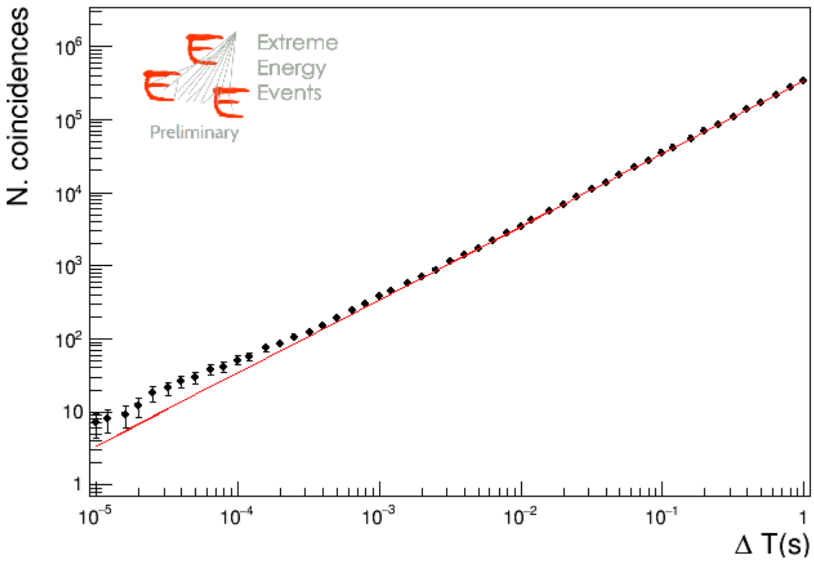

Figure 4. Number of coincident events (in black) as a function of the time window, compared with the expected number of accidental coincidences (red line). The error bars are due to statistical uncertainties. Additional information is given in the text.

collected during five coordinate runs. Several results were already published and refined analyses are currently ongoing.
Another successful aspect of this Project is its innovative outreach approach: high school students are directly involved in the experiment and they play a primary role starting from the detector construction.
The EEE Project is still expanding with the goal of enlarging the array and involving more schools in the EEE network: an upgrade of the experiment is currently ongoing, aimed at reducing the operating high voltage, adopting eco-friendly gas mixtures and designing custom electronics for the trigger system and GPS unit [16].

References

[1] EEE Project web site: https://eee.centrofermi.it
[2] Centro Fermi web site: http://www.centrofermi.it/
[3] INFN web site: http://home.infn.it/it/
[4] CERN web site: https://home.cern/
[5] An S *et al* (EEE Collaboration) 2007 *Nucl. Instr. and Meth.* A **581** 209
[6] Abbrescia M *et al* (EEE Collaboration) 2018 *JINST* **13** P08026
[7] EEE DQM webpage: https://eee.centrofermi.it/monitor
[8] Abbrescia M *et al* (EEE Collaboration) 2011 *Eur. Phys. J. Plus* **126** 61
[9] Abbrescia M *et al* (EEE Collaboration), *PoS (ICRC2015)* 097
[10] Abbrescia M *et al* (EEE Collaboration) 2015 *Eur. Phys. J. Plus* **130** 187
[11] Abbrescia M *et al* (EEE Collaboration) 2013 *Eur. Phys. J. Plus* **128** 148
[12] Riggi F *et al* (EEE Collaboration) 2017 Il *Nuovo Cimento* C **40** 196
[13] Abbrescia M *et al* (EEE Collaboration) 2018 *Eur. Phys. J. Plus* **133** 34
[14] La Rocca P *et al* (EEE Collaboration) 2019 *Nucl. and Part. Phys. Proc.* 306308 175182
[15] Gerasimova N M and Zatsepin G T 1960 *Sov. Phys. JETP* **11** 899
[16] Abbrescia M *et al* (EEE Collaboration) 2019 *JINST* **14** C08005