



The extreme energy events project

Bring science inside schools

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Abstract The Extreme Energy Events Project is an experiment devoted to the study of cosmic ray physics. It consists in a network of about 60 detectors based on the Multigap-Resistive Plate Chamber technology, distributed in the Italian territory and at CERN. In particular, the detectors are installed in high-school buildings, and the scientific activity is carried on in strong cooperation with students and professors. In this perspective, the project relies on citizen science, since non-professional people are fully involved in the constant monitoring of the operations. Furthermore, students participate in many stages of the scientific process, from the building of the detectors at CERN to the installation and commissioning of the telescopes inside their schools, to data collection and analysis, and to publication and dissemination of results.

1 Introduction

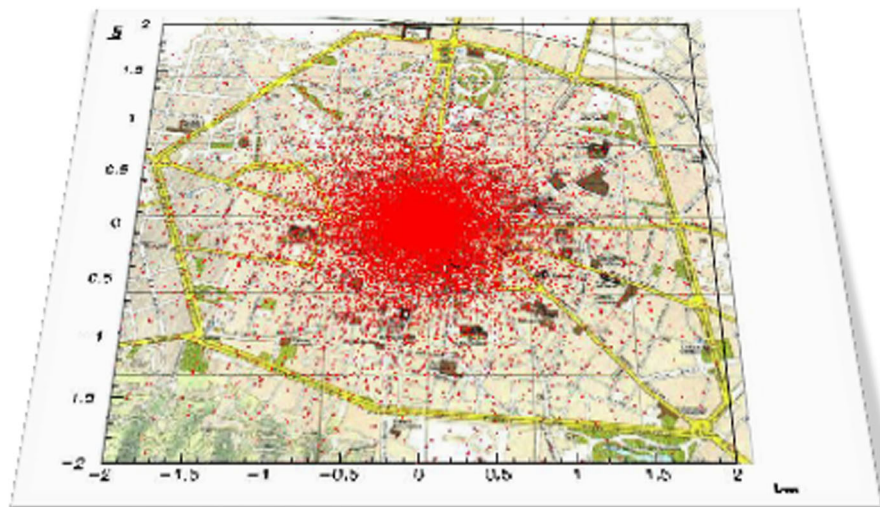
In its more general definition, citizen science is the involvement of the public in scientific research. It has been recognized as a strategic initiative, whose goal is to bring scientific awareness in the society. The COVID-19 pandemic proved how important it is to have an educated society, able to properly absorb scientific concepts, as the ones encoded in the statistical information it has been exposed to during the years 2020–2021. While standard dissemination procedures served as an important tool, so far, in bringing scientific ideas to the public, and updated people on the progresses of science in the different disciplines, from medicine to physics, the question remains on how to make people not only familiar with scientific notions, but really able to practice science in their everyday life. As an example, the ability to understand basic statistical concepts as frequency, conditional probability and margin of errors would play a relevant role in defining one's behaviours in a risky situation as the pandemic is, and properly tell between the risk of getting the COVID-19 in the most serious forms or suffer for possible collateral effects of vaccination. To reach this goal, people cannot be simply exposed to science, but have to practice it with an active involvement in professional projects. From these considerations, citizen science is acquiring a dominant role, proposing different initiatives in which people are directly involved in data analysis, data collection, etc. In this context, even more crucial than the awareness of adults is the awareness of young people. Beyond the obvious importance of educating next generations to science, they can also be more reactive to inputs coming from the scientific community, given their capability of easily develop familiarity with modern technologies.

With this goal in mind, the Italian Extreme Energy Events Project was designed in the early 2000s with the two-fold ambition of bringing science into the life of high-schools students and organizing an experiment on cosmic rays with the maximum area covered by a network of detectors. In order to achieve these goals, a coarse installation of well-equipped stations, with a coordinated data-taking system and well distributed all over the Italian territory was necessary. A continuous, well-organized monitoring system that allows to check the status of the network and let promptly intervene in case of problems was also mandatory. This ideal scenario was implemented through the decision of installing the detectors inside high schools all over the Italian territory, involving in this way, for the first time ever, also students and their teachers in a modern experiment within a unique outreach program. In this perspective, the project fully relies on citizen science, since the collaboration of students and teachers plays a dominant role in assuring the operational condition of the network. They are, in fact, involved in the constant monitoring of the detectors. Furthermore, students participate in many stages of the scientific process, from the building of the detectors at CERN to the installation and commissioning of the telescopes inside their schools, to data collection and analysis, and to publication and dissemination of results.

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Fig. 1 Simulation of a very high energy shower (10^{17} eV) perpendicularly impinging on the city of Bologna and producing 1 million secondary muons on ground shown as red dots



2 A network for detecting cosmic ray showers

The Extreme Energy Events (EEE) Project is an extensive experiment finalized to the detection of secondary cosmic rays [1]. The latter are particles produced by the primary radiation—fully ionized nuclei of all the known elements, mostly protons and light nuclei—when they hit the Earth atmosphere. In passing through the medium, indeed, they interact and produce different secondary particles that, travelling for many kilometers, eventually get to the ground where they can be observed by properly equipped stations. A single, primary cosmic ray can produce a shower of up to several millions of particles, and the print on the ground can shed light on the nature of the primary particle producing it. The distribution of the particle hits can cover an area of many squared kilometers, and it increases as a function of the energy of the primary particle. In view of this, in order to detect and reconstruct a shower produced by highly-energetic particles, a detector system covering a very large area is mandatory. As an example, a primary proton with an energy of 10^{17} eV hitting the atmosphere at an altitude of 15 km can produce a secondary shower completely covering a city as big as Bologna (Italy), as shown in Fig. 1.

The EEE network consists of about 60 detectors, the so-called “EEE telescopes”, spread all over the Italian territory, including the islands, and also in Switzerland (at CERN). Most of these telescopes are installed in high schools, as shown in Fig. 2. Tens of high schools without telescopes are also involved in the EEE Project and participate in the EEE meetings and activities, as it will be described later on (Sect. 5). The project has been launched and funded by the “Enrico Fermi” Historical Museum of Physics and Study and Research Centre [2], and it is now operated in collaboration with the Italian National Institute for Nuclear Physics (INFN) [3], CERN [4], and several Italian universities. As such, it is fully funded by the public research system. Every station of the network consists in a telescope composed of three layers of Multi-gap Resistive Plate Chambers (MRPCs), each having a sensitive area of about $80 \times 160 \text{ cm}^2$ (see Fig. 2). Before proceeding to the installation in a high-school, preliminary security conditions are verified in cooperation with the school referent for security. A proper aeration is mandatory, together with an access system that allows the entrance to the room where the station is installed to trained people only (Fig. 2).

A MRPC is a stack of glass plates, separated from each other with a spacer pattern made of common fishing line, enclosing six 250 or 300 μm gaps where the gas circulates, as shown in Fig. 3. They are readout by means of 24 copper strips each, $180 \times 2.5 \text{ cm}$ in dimension, pitched by 7 mm, connected to a suitable front-end electronics. They are enclosed in gas tight metallic boxes, $220 \times 110 \text{ cm}$ of external dimensions, and $192 \times 92 \text{ cm}$ internal. Chambers are powered by high voltage (around 20 kV), that is provided through a DC/DC converter system (two for each chamber) that transforms the low input voltage to the 10 kV applied to the external glasses, coated with resistive paint. With this solution, only low-voltage cables are present externally in the room. In between the external glasses, a proper gas mixture at atmospheric pressure provides the active medium. The anode and cathode strips collect the signals induced by the particles, providing position information along one direction. The information along the other coordinate is obtained by measuring the time delay between the signals arriving at the two ends of a strip.

Each station is also equipped with a weather station monitoring atmospheric conditions as pressure and temperature, that serve as input for correcting the measured charged particle rates. The GPS system is used to tag the time of arrival of good particles, allowing, in this way, a coordinated analysis between different stations in the search of distant correlated events. The status of the network can be monitored online through a Data Quality Monitoring interface, a web tool [5] that allows to check, almost in real time, the performance of each individual station and the quality of the reconstructed data. At the same time, a dedicated interface provides access to the full set of reconstructed data, that can be used to perform high-level analysis.



Fig. 2 Left: the EEE network. Red and orange dots indicate the positioning of the EEE stations, in high-schools and at CERN or INFN laboratories, respectively. Cyan dots indicate the location of the schools participating in the project without a telescope. Right: a telescope installed in a high school

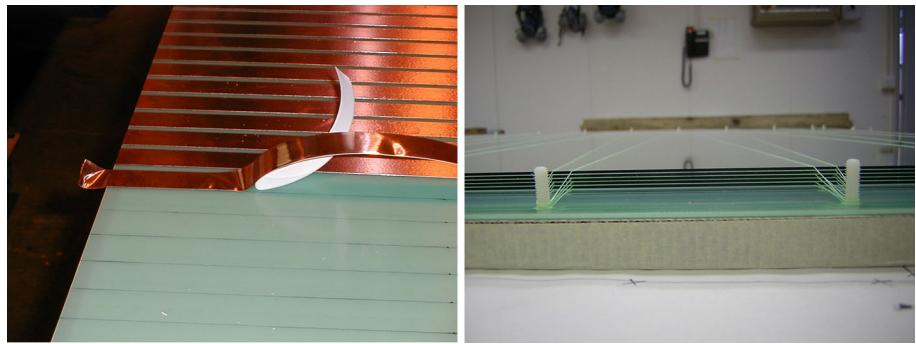
3 Scientific results and activities

The excellent performance of the detectors allowed the EEE Collaboration to perform relevant measurements in the field of cosmic-ray physics, based on the detection of the secondary muon component. Presently, different lines of research are being carried on. Beyond the observation of the Extensive Air Showers (EASs), which has been already published by EEE in [6, 7], studies have been focused on the search of possible anisotropies at the sub-TeV scale [8], as well as on the measurement of upward-going particles [9]. Furthermore, the great coverage of the observatory, spread out in all the Italian territory, together with the continuous data taking from September to June (but also during Summer, if the room where the station is located is properly air-conditioned) allowed to detect and analyze solar phenomena as the Forbush effects [10, 11], and to search for long distance correlations among detectors located from few to hundred kilometers apart [12, 13]. The latter measurement is being updated with the inclusion of the statistics collected during the last years of operation.

In addition to physics measurements, different performance studies have been carried out [14, 15], that proved the robustness of the detectors, operated in unconventional working sites, and the resistance to ageing of the MRPC technology. The results of the analysis on the performance of the network are fully compatible with the EEE requirements in terms of efficiency (93%), time resolution (238 ps) and spatial resolution (1.5 and 0.9 cm respectively for longitudinal and transverse direction). In order to better understand detector systematics, and to get a full characterization of the performance of every station, a dedicated simulation tool has been developed [16]. MRPC geometry, materials and a parametric response of the detectors have been implemented in a user-friendly interface to GEANT4 libraries. The framework includes a cosmic muon event generator based on an improved Gaisser parametrization of the muon flux at the Earth level, and has been validated by a detailed comparison to single-muon rates (angular and integrated) recorded by some selected EEE telescopes. The agreement between experimental data and simulated data is at few percent on several observables (absolute cosmic rate, angular distributions, resolution,...), proving the validity of the simulation.

In parallel to standard operations, a new upgrade campaign has been started in order to substitute the presently adopted gas mixture with an eco-friendly solution [17]. The recent restrictions on greenhouse gases, indeed, demand studies for new gas mixtures in compliance with the relative requirements. Tetrafluoropropene is one of the candidates for tetrafluoroethane substitution, since it is characterized by a Global Warming Potential around 300 times lower than the gas mixtures used up to now. Several mixtures have been tested, measuring efficiency curves, charge distributions, streamer fractions and time resolutions. The most promising mixtures are being used on selected stations, and preliminary results on their performances will be soon released.

Fig. 3 Left: application of copper tape on the vetronite panel, that will constitute the readout electrodes. Right: a 250- μm diameter fishing line is stretched across the surface of the glass from one side to the other and around plastic screws fixed at both sides of the chamber. It will serve as spacer between glass sheets



4 Chamber construction, monitoring of the station performance and data analysis

The involvement of students in the EEE Project covers all the aspects of a scientific project, and starts with the building of the detector at CERN [18] (see Fig. 3). A selected group of students and a teacher is invited at CERN to take part in the construction of the three chambers that will equip the detecting stations. During the five days of the construction, each team builds the three MRPC detectors that will constitute the station to be installed in their institute. They use common materials such as glass, plastic and fishing lines (see Fig. 3, right). More in details, each MRPC ($0.8 \times 1.6 \text{ m}^2$ active area), is a stack of resistive plates working in a streamer-free operation mode. It consists of six gas gaps of $250 \mu\text{m}$, filled with a 98% $\text{C}_2\text{F}_4\text{H}_2$ and 2% SF_6 gas mixture. The resistive plates are commercially available soda lime glass with a thickness of 1.9 mm for the outer glass sheets and 1.1 mm for the inner sheets. The external glass sheets are coated with a resistive paint to create a resistive electrode with a surface resistivity of about $5 \text{ M}\Omega/\text{Squared}$. MRPC are powered through a high-voltage system based on DC/DC converters, which supply up to 10 kV when powered with 0–5 V. The signal initiated by a charged particle traversing the detector is formed on the 24 readout copper strips; these are obtained by applying copper tape (2.5 cm wide) on vetronite panels (see Fig. 3, left).

The signal then drifts to both ends of the MRPC where they are read by front-end cards (24 channels each) provided with an ultra-fast and low power amplifier/discriminator designed for MRPC operation: the NINO ASIC chip [19]. Totally, 144 channels are used for each telescope and time measurements are performed through commercial multi-hit TDCs. Two honeycomb panels (15 mm thick) reinforce the structure which is then enclosed in an aluminum box provided with standard gas connectors. After the construction, the detectors are brought to Italy and commissioned in their final location—typically a high school—where, once working conditions are reached, the telescope is connected to the coordinated data taking system and students can start a monitoring activity. In particular, they perform daily checks to monitor the proper functioning of the detector. This latter aspect plays a relevant role, especially during periods of coordinated data taking when the number of working stations has to be kept as high as possible.

Beyond the initial phase tests, students routinely perform checks of the operating conditions, e.g. verifying the telescope orientation to correct muon arrival direction (essential to relate a track to another one registered on a different telescope of the network) or characterizing the telescope by measuring its efficiency.

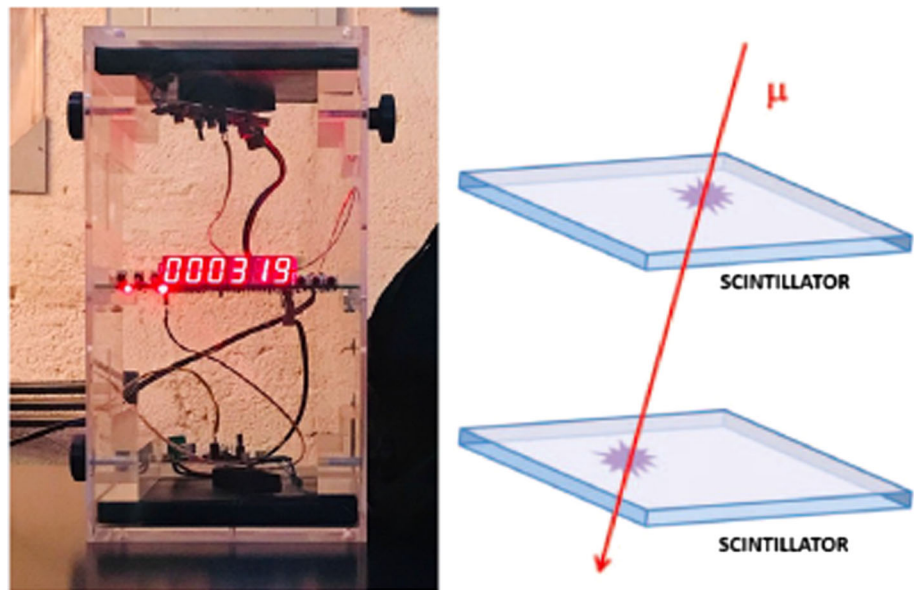
In addition to it, students and teachers can monitor the quality of the collected data by analyzing the relevant distributions, verifying, for example, how many adjacent strips have been fired by passing tracks, what is the average hit multiplicity of a given run and the time distribution of the events passing the trigger selection. Following this *in loco* evaluation, students can operate on the network data also independently, by accessing all the reconstructed data that are made available through a web-tool that allows to have a further look into the registered events.

Students are also actively involved in data analysis. They get familiar with professional tools used in the high-energy physics community as, e.g., ROOT [20], and attend masterclasses on statistics routinely organized by the EEE researchers. They apply then the concepts they have learned in measuring the speed of the muons, in performing acceptance studies to understand the angular coverage of the detector, or analyze differences in the observed rates to estimate transitory effects as the Forbush decrease.

5 Meetings and other activities

An essential part of the research experience is the regular participation in meetings and conferences. In order to offer to the EEE students the possibility to experience this crucial aspect, researchers from the EEE Collaboration organize, on a regular basis, meetings and conferences, both online or in presence. During these meetings, students interact with researchers and other students. They present their works, exchange ideas on how to face possible problems, and plan future activities. A Run Coordination Meeting, in which all the nearly hundred high schools (with or without telescopes) of EEE participate, is organized on a monthly basis. During it, in addition to the presentations by schools, talks on general aspects of physics are offered to the students, as well as masterclasses on possible topics of interest for the scientific activity within the experiment (ROOT [20], statistics, data quality monitoring). In addition to this online event, twice per year a meeting in presence is organized either in Erice, at the Ettore Majorana Foundation

Fig. 4 Left: the cosmic box used to carry out the measurement of the cosmic ray variation with altitude. Right: working principle of a cosmic box



and Centre for Scientific Culture, or in one of the cities hosting an EEE institute. This in-presence meetings offer the possibility not only to teach students how to properly present their work, but also to involve them in actual measurement campaigns. One of these was devoted to the measurement of the muon flux at different altitudes, which led to an educational publication [21], while another, whose goal was to replicate the Eratostene experiment, produced an estimation of the Earth radius [22]. For the first measurement, the so-called “cosmic box” is used. It is a portable device composed of two scintillator layers ($15 \times 15 \times 1 \text{ cm}^3$ each in dimensions) placed at a distance of 30 cm (see Fig. 4). Charged particles crossing the scintillator layers deposit in them part of their energy and produce a light signal. The latter is properly collected and converted to an electric signal through a photo-sensor. The adopted solution is based on plastic scintillator (model EJ200) produced by the Eljen Technology [23], characterized by an absorption length equal to 380 cm and provided with a good time resolution. The light yield is read by the NUV3S-P Silicon PhotoMultiplier (SiPM) by ADVANSID, with a surface of $3 \times 3 \text{ mm}^2$ and pixel size equal to $40 \mu\text{m}$ [24]. The emitted light spectrum is peaked around 425 nm, that corresponds to the region where the efficiency of the photo-sensor is maximal. To optimally redirect the light to the photo-sensor, the scintillator planes have been entirely covered with a reflecting material and enveloped with black tape, so to screen external light. The device is equipped with a dedicated readout electronics, that allows to set the preferred trigger. It can be operated, indeed, by acquiring signals occurring on single layers only or simultaneously on both. With the chosen configuration in terms of plane distance and equipment, at the sea level the expected coincidence rate is equal to 0.5 Hz. The cosmic box is powered by 5 V voltage, that can be provided through a jack or by a USB connector, the latter solution allowing the usage of the detector in open environments, where commercial power banks can be used to power it. Ten of these portable detectors are available within the EEE collaboration. In order to make the research experience of students complete, on a yearly basis a contest is organized in the EEE Collaboration, the so-called Cosmic Box Contest. In its conception, it mimics the strategy adopted by the different research agencies, that make support (in the form of funds, facilities, instrumentation) available for research projects selected through a proper procedure. In a similar way, the opening of the contest is announced to the EEE participating institutions, that, in order to get a cosmic box for a certain amount of time, have to prepare a research proposal based on this device. The proposal should motivate the scientific relevance of its content, illustrating the reasons beyond the place chosen for the measurements, that can span from peculiar geological or naturalistic environments (caverns, lakes, mountains...) to historically relevant sites (archeological buildings etc, where also the material used in the construction can affect the results). The project should also provide proper considerations on the amount of data they want to collect: the exposure time is strongly influenced by the effect to be estimated, since it directly translates into the expected precision of the measurements. In preparing such a proposal, students understand how strategic is the designing phase of an experiment, and how many factors enter into the definition of a proper measurements campaign. As in the real life, where research is worldwide organized in networks of several institutions, cooperation between institutes is also strongly encouraged, and proposals can be submitted as joint ventures between different schools.

Another relevant initiative where students are involved is the PolarQUEEEst experiment [25]—inspired by the historical scientific expeditions in the Arctic—where a boat sailed through the Svalbard archipelago, getting to a latitude of $82^\circ 07' \text{ N}$ and performing a set of multidisciplinary experiments (PCBs, polychlorinated biphenyls, micro- and nano-plastics, polar drones). The EEE Collaboration was responsible for the measurements of the cosmic ray flux up to the far North latitudes, and, to this end, a portable cosmic ray detector, POLA, was designed [26–28], with students actively participating in the detector construction.

Students also take part to international events, as the *International Cosmic Day*, a yearly event organized by the *Deutsches Elektronen-Synchrotron* (DESY), where students, teachers and scientists meet to discuss about cosmic rays. EEE students participate

in the initiative presenting measurements on relevant cosmic ray observables, as the speed of muons, the angular distributions of secondary cosmic rays or rate variations as a function of different quantities. This occasion widens the audience the students address, and offers them the possibility to compare their activity with the ones carried out by schools in other parts of the globe.

6 Conclusions

A proper scientific education in society is emerging, in present times, as a crucial aspect. Having a citizenship able to grasp basic scientific concepts and assume science-oriented behaviours is a mandatory fact for nowadays countries, since it allows to understand, and accept, future-oriented strategies, as the ones that the latest emergencies proved to be necessary. However, while education to general ideas can be obtained through standard outreach initiatives, to get a population fully aware of scientific methods and willing to adopt them in any circumstance proved to be a harder task. Indeed, only a direct involvement of people in science can bring them to a full comprehension of the power of the Galilean method. In view of this, citizen science, i.e. the “*scientific work undertaken by members of the general public, often in collaboration with or under the direction of professional scientists and scientific institutions*” [29], is an essential concept that has to be implemented in the everyday life of researcher professionals. In fact, they have to honor their scientific mission not only performing researches at the edge of knowledge, but also explaining to people the importance of their work and, whenever it is feasible, involving them in part of their activity. In this global scenario, the Italian EEE Project, in its two-fold nature of a scientific experiment and an outreach initiative, offers a unique environment for initiating students to scientific research, directly bringing them into all the different aspects of a modern experiment in particle physics, and educating future generations to the practice of science.

Data Availability Statement No Data associated in the manuscript.

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