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Operation and performance of the EEE network array for the detection of cosmic rays

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ABSTRACT

The EEE (Extreme Energy Events) Project is an experiment for the detection of cosmic ray muons by means of a sparse array of telescopes, each made of three Multigap Resistive Plate Chambers (MRPC), distributed over all the Italian territory and at CERN. The main scientific goals of the Project are the investigation of the properties of the local muon flux, the detection of Extensive Air Showers (EAS) and the search for long-distance correlations between far telescopes. The Project is also characterized by a strong educational and outreach aspect since the telescopes are managed by teams of students and teachers who had previously constructed them at CERN. In this paper an overall description of the experiment is given, including the design, construction and performance of the telescopes. The operation of

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MRPC
Telescopes
Physics education

the whole array, which currently consists of more than 50 telescopes, is also presented by showing the most recent physics results.

1. The EEE Project

The EEE Project studies cosmic ray muons by means of a sparse array of cosmic ray telescopes installed over the Italian territory [1,2]. The Project is coordinated by the *Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi – Rome* [3] with a joint effort of several research centers, such as the INFN and CERN.

The use of a sparse array of detectors allows to investigate several aspects of cosmic ray radiation: first, each single telescope gives information about the local flux of cosmic muons, which is known to be influenced by several aspects, such as weather effects or sudden solar events; second, telescopes placed in the same metropolitan area can be used to identify EAS events; third, telescopes placed hundreds of kilometers apart can ideally detect long-baseline correlations caused by two (or more) time-correlated EAS originated by a common mechanism.

In addition to this research activity, the EEE Project conducts an intense outreach programme in Italian high schools. Hundreds of students and teachers have been involved in the experiment over the last 10 years, taking part in the construction, installation and use of the detectors. Moreover, the choice of installing the telescopes in the schools produced a double benefit: it provided a natural selection of suitable sites where to install the telescopes (the schools are well-distributed over the Italian territory) and it allowed students to take care of data taking and maintenance of the telescopes.

In this paper we will mainly focus on the operation of the detectors, reported in Section 3. A brief description of the detectors is given in Section 2, while some examples of data analyses, made possible given the excellent performance of the EEE telescopes, are described in Section 4.

2. Description of the detector

The detector technology chosen for the experiment had to fulfill several design requirements, such as long-term operation, high detection efficiency, good time and spatial resolution. Moreover each detection station has to reconstruct the orientation of the incoming particles. The final choice was a telescope made of three MRPC [4], whose design is a larger ($160 \times 80\ cm^2$) and simpler version of the MRPC developed for the ALICE time of flight detector.

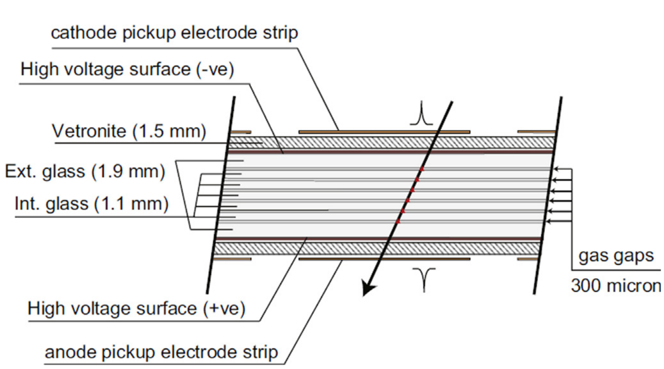

Fig. 1. A schematic representation of the EEE MRPC. A differential signal is obtained by reading out both anode and cathode.

Each chamber consists of a stack of resistive (glass) plates, spaced by 300 μm. The voltage (~20 kV) is applied only to the external surfaces, coated with a special resistive paint. The gaps are continuously flushed with a gas mixture (98% of $C_2H_2F_4$ and 2% of SF_6), optimized to achieve a detection efficiency close to 100%. Within each gap the passage of a charged particle induces electron avalanches due to ionization processes in the gas. Readout copper strips are mounted on two vetronite sheets, one placed above and one below the stack of glass plates. In total there are 24 strips for each side with 3.2 cm pitch. The induced signal on the pickup electrodes is the sum from all electron avalanches in all the gas gaps. A schematic representation of the six gap EEE MRPC is shown in Fig. 1.

The signals induced on the pickup electrodes are read out by Front End electronics boards based on NINO-ASIC [5] at the two opposite short sides of the chambers. From the front-end cards a total of 144 LVD signals are fed into two commercial multi-hit TDCs, which provide time measurements with 100 ps precision in a time window of 500 ns.

Each MRPC can reconstruct the impact position of the incident particles: one coordinate is given by the firing strip, while the other is obtained by the time difference of the signal at the opposite sides of each strip. Uncertainties in the position of the hits along the muon track directly affect the reconstruction of the particle direction. More details about the technical parameters of the chambers can be found in [4].

3. Chamber and telescope performance

The performance of the EEE detectors has been measured both at the CERN PS test beam facility and during normal operation using cosmic ray muons. Details about the experimental setup and analysis procedures adopted have already been reported in previous papers [4,6]. In this section we report a summary of the main performance characteristics of the EEE telescopes.

Efficiency: The data acquisition trigger in each telescope is provided by a six-fold coincidence of both front-end cards of the three MRPCs. As a consequence, in order to have an overall high detection efficiency, each MRPC has to detect incident particles with an efficiency close to 100%. The MRPC efficiency depends on the gas mixture chosen as well as on the HV applied. During the commissioning of each telescope, the detection efficiency of the MRPCs is measured with the help of two external scintillators that provide a trigger on cosmic muons passing through the chamber under test. This measurement is replicated periodically, to test the stability of the telescope in terms of efficiency and to involve high-school teams in advanced experimental activities. The measured MRPC efficiency is typically 95%. This result is compatible with the first measurement performed at the CERN PS beam facility [4]. The dependence of the efficiency from the applied HV has been reported for example in Refs. [2,6–8].

Spatial resolution: The EEE MRPCs were designed in order to have a spatial resolution of the order of 1 cm. Since the procedure used to reconstruct the hit coordinates is different for the long (X) and short (Y) coordinate of the chamber, it was necessary to perform two separate measurements of the spatial resolution along X and Y directions. During the CERN beam tests [4], the

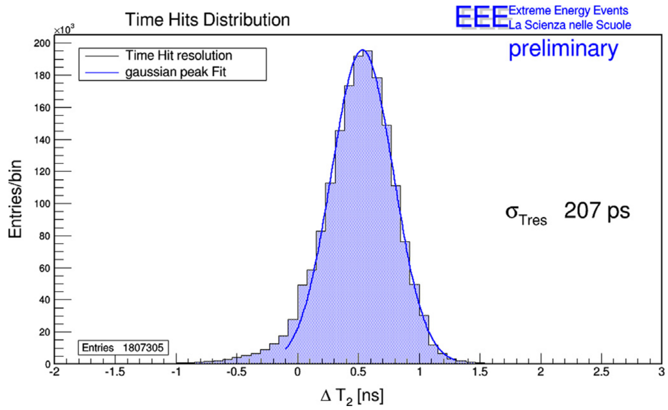

Fig. 2. Residuals between the time measured in the middle chamber and the time predicted by using the top and bottom chambers. The 500 ps shift is due to the fact that the strip intercalibration was not optimized.

spatial resolution along the X coordinate of one EEE MRPC was measured with high accuracy: the value depends on the position along the strip and varies from 0.7 cm to 1.2 cm. A less precise measurement has been repeated with cosmic rays at schools by using the top and bottom chambers to predict the position of the track in the middle chamber. The position resolution along the Y direction turned out to be 1.0 cm, in good agreement with the strip pitch constraint ($\sigma_Y = 3.2\text{ cm}/\sqrt{12}$). Along the strip direction the measured resolution was 1.9 cm, slightly worse than the design specification. However many factors can affect this result, such as chamber misalignment, strip-by-strip miscalibration or multiple scattering suffered by low-energy particles. Work is ongoing to reduce some of these factors and optimize the measurement.

Time resolution: The possibility to perform a rough measurement of the Time Of Flight (TOF) of the incoming particles improves considerably the quality of some data analyses, as discussed in the following section.

The TOF measurement between the top and bottom chambers can be performed thanks to the very good time resolution of the EEE chambers, which was measured for the first time during the PS beam tests [4]. Just like the spatial resolution, also the time resolution depends slightly on the position along the strips, ranging from 65 to 80 ps. This result has been obtained by correcting the data for a time slewing problem due to the use of discriminators with fixed threshold. The time resolution of the chambers has also been measured at schools. The result, shown in Fig. 2, is consistent with what is expected for cosmic rays. It should be noted that no correction for time slewing was applied to the data.

Track reconstruction capability: The precision in the hit position reconstruction defines the tracking capabilities of the telescope. Geometrical simulations demonstrate that the directions of particles crossing the EEE telescopes are reconstructed with an error of 0.9°, which is a satisfactory result for the analyses carried out with the EEE telescopes.

Together with the particle orientation, the telescope can also provide a rough value of the particle speed (calculated via the measurement of the track length and the TOF). The resolution on β is a direct consequence of both time and spatial resolutions. Fig. 3 shows the $1/\beta$ distribution measured on a sample of events collected by one of the telescopes installed in Frascati near Rome (named FRAS-02): the width of the peak indicates a resolution on $1/\beta$ of the order of 10%. One can also see that the distribution is not perfectly symmetric and the presence of a tail in the region $1/\beta > 1$ indicates a significant component of relatively slow particles.

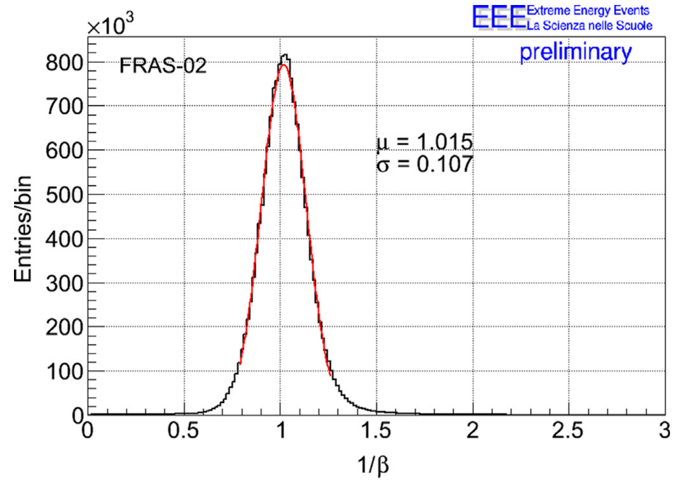

Fig. 3. $1/\beta$ distribution relative to tracks reconstructed by one EEE telescope over a period of ~3 weeks.

4. Physics results

Preliminary results from the EEE Project have been already reported during the past years [9–12]. In 2014 the EEE Project received a new boost with the organization of simultaneous and centralized data taking with the whole telescope array. The first centralized run (Pilot Run) lasted less than 3 weeks and involved about 20 telescopes. It was followed by Run-1 in 2015 (from February 2 to April 30) with the participation of 35 telescopes in the data taking and in about 3 months more than 5 billion events were collected. Run-2, still ongoing, started at the end of October 2015 with the goal to achieve 15 billion tracks in 7 months by using 40 telescopes.

The data are automatically transferred and stored at the INFN-CNAF computer centre in Bologna, where a software architecture has been set up to reconstruct the data and provide histograms on the web for monitoring purposes [13].

The new statistics now available has opened up the possibility for new studies and has improved the quality of the preliminary results already published such as the detection of EAS [12] or the study of Forbush decreases [8,10]. In this section we will focus on a few examples of data analyses, trying to emphasize the importance of the telescope performance already discussed.

The capability to reconstruct the direction of the incoming particles allows the EEE telescopes to measure small but

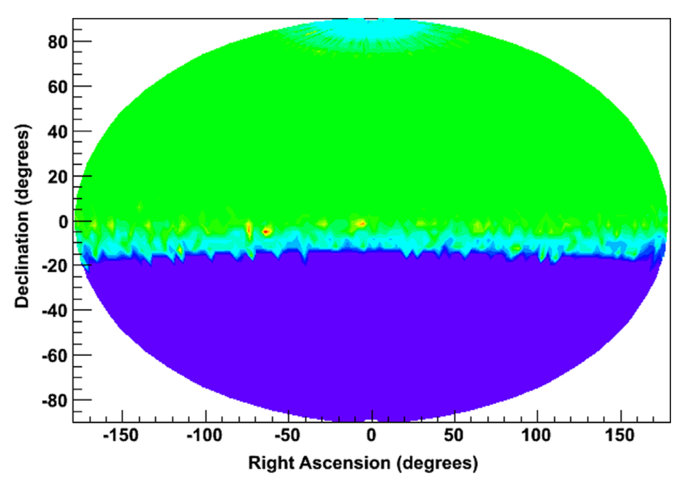

Fig. 4. Aitoff projection of the sky map summed over a first set of about 110 M events, collected by 4 different EEE telescopes.

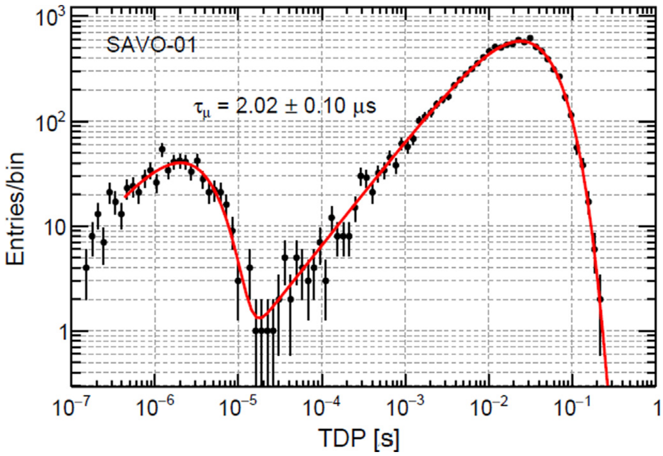

Fig. 5. Time difference between 2 consecutive events, with no cuts on the speed of the previous event. The plot shows 5 days of data collected by one EEE telescope.

measurable anisotropies in the arrival distribution of cosmics over a wide portion of the equatorial sky. Since most of the muons detected at sea level come from EAS in the energy range $10^{10}-10^{12}$ eV, the inclusive angular distribution measured by the EEE telescopes can be used to inspect the magnetic field structure in the interstellar environment close to our Solar System. A small amount of data collected during the Pilot Run was already used to evaluate the experimental conditions under which the observation of the sub-TeV sky map may be carried out by using the EEE telescopes [14]. Fig. 4 shows the sky map, in Aitoff projection, obtained from a first set of data collected by several EEE sites. The data have been corrected for the time exposure of the telescopes and their geometrical acceptance. The map is compatible with an isotropic distribution at the level of $5\times10^{-3}-10^{-2}$ in the declination range between 20° and 60° where border effects (due to low statistics) are negligible. This preliminary study will be followed by a more accurate analysis that is currently ongoing on a larger sample of events.

Another intriguing study performed with the EEE telescopes concerns particles crossing the telescopes and directed upwards from the ground [15]. These events are relatively rare if compared with downward-going tracks. Most of them are caused by the decay of cosmic muons in the material below the telescope. To identify the particles detected, it was necessary to apply stringent cuts on the β of the particles and on the quality of the track fit. In this way it was possible to select a clean sample of upward-going electrons coming from the decay of slow downward-going muons. From the time difference with respect to the previous event (TDP), it was possible to perform a measurement of the muon lifetime, as shown in Fig. 5. The peak on the right is due to two consecutive not correlated downward-going muons and the related TDP is dictated by the rate of data acquisition. The peak on the left is the result of a downward-going muon followed by the upward-going electron produced by the muon decay; for this class of events the TDP can provide a measurement of the muon lifetime. For more details on the analysis see [15].

In principle, some of these upward-going events could also be related to neutrinos crossing the Earth and interacting close to its surface just under the telescopes but considerable statistics would be needed to study these rare events. The new statistics now available and some improvements in the reconstruction procedure will lead to an even more refined analysis in the future.

5. Conclusions

The EEE Project network currently consists of more than 50 telescopes that are continuously taking data in Italian high schools. The performance of the telescopes has been extensively studied and the results are in good agreement with the design specifications. Many data analyses have already been published and many others are still in progress.

In the future new schools, and consequently new telescopes, will be added to the EEE array. In addition to its scientific value, the EEE Project is succeeding in introducing a large number of high school students to scientific research.

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