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Search for coincident air showers over large scale distances with the EEE network

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Abstract

The existence of time correlations in detectors separated by distances much larger than the size of the highest energy extensive air showers (EAS) has been long discussed over the years. Several mechanisms have been proposed to justify the existence of such events and, in the last decade, some experiments have also tried to search for correlations on a large scale distance, beyond one hundred kilometers. The approaches were based on the construction of clusters of detectors placed at large relative distances, with the capability of selecting extensive air showers.

Within this context, the Extreme Energy Events (EEE) experiment can provide new inputs in the search for long distance correlations, thanks to its sparse array of muon telescopes spanning all the Italian territory.

The EEE telescopes are taking data since more than 10 years and enough statistics has been already accumulated to be able to search for such events, whose observation is intrinsically difficult due to the very low rates expected, many order of magnitudes smaller than the overall cosmic ray flux. In order to reduce the accidental correlations, different analysis approaches have been investigated for the selection of EAS events with the EEE telescopes. In this paper we will present preliminary results obtained by analyzing a large fraction of the statistics currently available.

Keywords: Cosmic rays, extensive air showers, tracking detectors, MRPC

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1. Introduction

Since the discovery of their nature in the beginning of the 20th century cosmic rays have been an important subject of research both in the fields of astronomy and astroparticle physics. While lower energy cosmic rays ($E \lesssim 10^{14}$ eV) can be measured directly with particle detectors on balloons or space craft, higher energy cosmic rays are so rare that a detection with sufficient statistics needs detection areas larger than those provided by direct measurements. Thus, indirect measurement methods are used, based on the detection of extensive air showers (EAS) induced by cosmic rays. With this aim several huge detector arrays with large exposure have been built in the last decades to answer the open questions of ultra high energy cosmic ray physics, especially the question of their origin, flux, energy, arrival direction and mass composition.

The size and composition of an extensive air shower depends on the mass and energy of the primary cosmic ray and does not usually exceed few kilometers. For this reason most of air shower observatories in the world consist of a large number of particle detectors arranged in arrays with typical spacing distances of the order of 1 kilometer. However, in recent years, alternative detector configurations have been proposed, fostering the coverage of larger detection area at the cost of increasing the detector spacing distance. The main physics motivation for the use of sparse arrays lies in the possibility to search for time coincidences between different extensive air showers.

From a theoretical point of view, the possibility to observe cosmic rays time correlations between detectors separated by distances much larger than the extension of the highest-energy EAS has been long discussed over the years. Possible physical mechanisms which could justify the existence of such events have been proposed [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Among them, one of the most promising theories was suggested in 1960 by the Russian physicists Gerasimova and Zatsepin [1], who considered the possibility that an ultra-high energy cosmic nucleus is split into two parts due to an interaction with a photon coming from the sun which breaks the nucleus in two fragments. Because of the different electrical charges of the two remnants, they are deflected by the interplanetary magnetic field in a different way. If both these remnants reach the earth's atmosphere, they will create two separate air showers, arriving at essentially the same time and from the same direction, but with a certain separation between them. Such mechanism, named Gerasimova-Zatsepin effect (GZ-effect), is widely accepted in the scientific community but has not yet been experimentally confirmed. Since the current rate expectations range from 10^{-3} to 1 event per km^2 per year, large exposure sparse arrays and long data acquisitions are required.

Some experimental hints about the observation of large-scale coincidences between extensive air showers have been observed in recent years by LAAS [11, 12, 13] and CZELTA-ALTA [14, 15] Collaborations. In this respect the Extreme Energy Events (EEE) experiment, thanks to its many detection stations spread through the Italian territory, can give significant answers about the search for long-distance correlations.

A detailed description of the EEE netweork and its experimental setup is given in Section 2, while a discussion about the analysis strategies and the first preliminary results is addressed in Section 3.

2. The experimental setup

The main challenge in searching for large-scale correlations between EAS is strictly related to the low level of events expected per year. This results in specific requirements that the experimental setup has to fulfil to allow for this kind of study: in principle the overall observatory surface should be as large as possible, in order to be sensitive to the arrival of EAS separated by a distance that can span from tens to several hundreds of kilometers, depending on the masses and energies of the fragments generating the showers; the number and the position of the detection stations should be optimized to maximize the probability of detecting the extensive air showers hitting the observatory area; finally, the use of detection stations able to reconstruct the arrival direction of the fragments provides relevant information for the selection and interpretation of the recorded data.

Except for a few cases, most of the sparse arrays present in the world were born as a network of detectors installed at schools for educational purposes: the capillary presence of schools in a country makes such places an ideal location to be used as detection site of a sparse array for cosmic rays. In the last decade many educational projects were born aiming at the installation of particle detectors at schools, increasing the number of detection sites year after year and naturally building a tool even for the search for long distance correlations between EAS.

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Figure 1: Map of the detectors installed at schools (in red) and at universities or research centres (in orange). The schools that participate in the project without hosting a detector are represented in blue.

2.1. The EEE array

The EEE Project is an educational and scientific experiment born in 2004 from an initiative of the "Enrico Fermi" Historical Museum of Physics and Research and Study Centre [16, 17] in collaboration with INFN (Italian National Institute for Nuclear Physics), CERN and MIUR (the Italian Ministry of Education, University and Research). The project focuses on collaboration with secondary schools and gives students the opportunity to participate in a real scientific research.

Many participating schools host a cosmic ray telescope for the detection of secondary cosmic ray particles. A map of the 56 detectors already installed is shown in Figure 1: they form a sparse array covering an area larger than 3×10^5 km^2. In a few cases two or more telescopes are installed in the same metropolitan area. Thus, taking into account all the possible combinations between two EEE detectors, the EEE network covers a wide range of distances, ranging from 15 m up to 1200 km.

The research goals of the EEE experiment are not limited to the search for coincidences between EAS. Many results have been already published about the study of the properties of the local muon flux and its dependence on the Earth and solar environment, as well as about the detection of high-energy extensive air showers. A complete description of the experimental setup and recent physics results from the EEE Project are reported in [18, 19, 20, 21, 22].

2.2. The MRPC chambers and their performance

Each detector of the array is a telescope made of 3 Multi-gap Resistive Plate Chambers (MRPC) specifically designed for combining good tracking and timing capabilities, low construction cost and easy assembly procedures. The chambers are built at CERN by groups of students and teachers, under the supervision of researchers and technicians. After the construction and the test of the chambers, the telescopes are moved to high schools where the students and teachers actively participate in the data taking activities, taking care of the telescope operation and maintenance. Researchers supervise activities at schools, providing technical support and introducing the students to the problems and results of particle and astroparticle physics through seminars, lectures and master-classes.

Each MRPC has an active area 0.82×1.58 m^2 and is made of a stack of 7 glass sheets, spaced by 300 μm. The two external glass plates are treated with a resistive paint and are connected to high voltage (up to ±10 kV). A transverse section of the chamber is shown in Figure 2.

A gas mixture consisting of $C_2H_2F_4$ (98%) and SF_6 (2%) is continuously flowed within the chambers, at a continuous flow of 2 l/h and atmospheric pressure. The ionization charges produced in the gas gaps by the passage of the cosmic particles induce a differential signal on the pick-up electrodes, that are 24 copper strips (160 cm long, with a pitch of 3.2 cm) laid on the vetronite panels above and below the glass stack.

The EEE chambers can reconstruct the two-dimensional position of the particles since one coordinate is given by

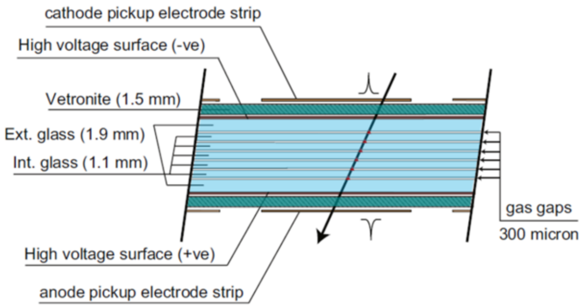

Figure 2: MRPC transverse section.

the position of the strip carrying the signal, while the other is provided by the time difference in the arrival of signals at each strip end.

In each telescope the three chambers are placed at typical distances of 50 cm, allowing the reconstruction of the incoming particle direction with a good angular resolution (in the order of 1 degree).

In order to combine information from the different telescopes, each event is tagged by means of a GPS unit which provides an absolute time reference with a precision in the order of a few tens of nanoseconds.

Detailed results of a systematic study of the EEE chambers performance can be found in [23].

2.3. Data acquisition and storage

After an initial period of construction and commissioning of the first telescopes in 2007, a coordinated data taking officially started at the end of 2014 with a three weeks Pilot Run, during which 1 billion of events were collected. Since then, the observatory has grown up in terms of number of telescopes and duty cycle. The coordinated runs performed so far are listed in Table 1.

RUN	Duration	No. of telescopes	No. of events
1	2 months	35	5×10^9
2	6 months	40	15×10^9
3	7 months	50	18×10^9
4	8 months	50	20×10^9

Table 1: List of the coordinated data taking periods in the EEE experiment.

The EEE network is currently the largest and longest-running detection system based on MRPC technology, with its 56 sites and 14 years of operation. By the beginning of 2019 about 100 billion tracks are expected to have been collected.

In order to deal with the increasing amount of data produced by the network, the EEE researchers have set up customized procedures for the transfer, storage, preprocessing and quality monitor of the data. Many tools have been developed exploiting the INFN CNAF cloud facility, in order to help students and teachers to monitor the status of their telescope, by checking the quality of the data through a dedicated web page [24] as well as daily filling a logbook with the main telescopes vital parameters.

The EEE facility is recently undergoing an upgrade phase that includes the construction of new chambers with reduced gas gaps, the use of a new gas mixture satisfying recent EU restrictions on the “Global Warming Potential (GWP)” limit, and the development of customized electronics modules. 20 new schools will be soon equipped with these upgraded telescopes, thus increasing the number of detection sites of the EEE network and providing larger statistics for physics analyses [25].

3. Search for long distance correlations

The possibility to experimentally observe large-scale correlations in cosmic rays has been almost disregarded over the years, although many theoretical mechanisms predicting their existence were formulated. It is worth mentioning that the observation of such events is not only useful to validate the theory, but it can provide an unconventional means to study the cosmic ray radiation: in 1951 Gerasimova and Zatsepin suggested their theory about the photodisintegration of cosmic rays in the solar photon field as a tool to make a prediction on the mass composition of ultra high energy cosmic rays.

In the following sub-sections a brief review of the methods and analysis procedures employed to search for long distance correlations between sparse detectors in the EEE experiment is reported.

3.1. Analysis strategies

Due to the small probability of detecting two coincident air showers, different analysis strategies have been investigated within the EEE experiment in order to deal with the undesired spurious coincidence events between detectors [26, 27].

The simplest approach would consider the correlation between single muon events detected by two independent telescopes. The main advantage of such choice would be the large statistics available, since the count rate of each individual EEE telescope is of the order of 10−50 Hz. However, even applying a selective cut on the relative orientation between the detected muons, the spurious coincidence rate between a pair of telescopes would be of the order of 0.1−0.01 Hz in a time window of 1 ms, widely larger than the expected rate of the correlated EAS events.

In order to apply a more selective trigger on the class of events to correlate, two possible approaches can be pursued. The first consists in limiting the analysis on the correlation between those detection sites where at least two telescopes are installed in the same metropolitan area: these sites are hence able to detect extensive air showers by selecting coincidences between the close telescopes. The observed frequency of detection of extensive air showers varies between 0.001 and 0.04 Hz, depending on the relative distance between telescopes (ranging from 15 m to few kilometers). With this strategy, the accidental coincidence rate in a time window of 1 ms goes down to the level of about few events per year on average.

The second alternative approach is based on the possibility to detect multi−track events in each EEE telescope: due to the large detection area of the MRPC chambers, in a small fraction of the events even two or more correlated particles may be simultaneously detected and tracked. These tracks can be produced by independent particles belonging to the same shower or by particles originated from nuclear interactions in the building surrounding the detector. Regardless of the specific mechanism of production, the multi−track count rate is of the order of 0.01 Hz and this helps in handling the huge amount of spurious coincidence events between far detectors (in this case of the order of few events per year in a time window of 1 ms), thus enhancing the probability of observation of rare events.

3.2. Analysis details and discussion of the results

The first attempt to search for long-baseline correlations was made analyzing the data from the EEE telescope clusters. At present 10 EEE sites are able to detect single EAS by correlating tracks from close telescopes, resulting in 45 possible pair combinations. The distances between these sites range between 86 km and 1200 km. A dataset corresponding to an overall period of 3968 days time exposure was analyzed. By correlating all events within the time window dictated by the distance between the sites under investigation, we evaluated the p-value (according to a Poisson distribution) to obtain such an event by chance. A few candidate events with unusually low p-value were observed: they are characterized by small values of the time difference and in some cases also by a small angular difference. More details about this analysis can be found in Ref. [26, 27]. The main disadvantage of such analysis strategy is the reduced dataset available, that is limited by the number of EEE telescope clusters currently taking data. Compliant with its upgrade programme, the EEE experiment is now expanding its array through the installation of new telescopes, not only to add new sites to the existing network, but also to increase the number of sites with two or more telescopes in the same metropolitan area, that is now limited to 10.

Encouraged by these preliminary results, multi-track events were recently analyzed. In this case the statistics available is larger with respect to the previous analysis, since data from all the telescopes of the network can be used. Almost all the statistics available was processed, corresponding to the data collected from January 2016 to March 2018, for a total of 816 days (RUN2 + RUN3 + RUN4). During that period 39 telescopes were in operation, but each with a different duty cycle (sometimes sensibly smaller than 100%).

The first step of the analysis requires the selection of multi-track events. The study of events with multiple particles detected at short distances is one of the physics goals of the EEE experiment since it allows to investigate some properties of the atmospheric shower produced by the primary cosmic ray. For example, the distribution of the muon multiplicity in multi-muon events depends on the mass of the primary nucleus (protons or heavier nuclei up to Fe). An excess of multi-particle events compared to the results from simulations with widely used hadron interaction models, has been observed in a number of experiments performed with cosmic rays at high energies [28, 29]. In principle, this excess could be due to either cosmophysical (variations in the composition of the primary flux of cosmic rays) or nuclear causes (variations in the interaction between hadrons and the nuclei of air atoms). Some theoretical hypothesis suggest the possibility that such muonic bundles of highest multiplicity are produced by small lumps of Strange Quark Matter (SQM) colliding with the atmosphere [30].

Within the EEE collaboration the study of multi-track events has just started and no definite results have been produced so far. As a consequence the investigation of the long distance correlations, based on multi-track events, can be affected by the selection and quality criteria adopted to identify these events. The preliminary results discussed in this paper were obtained applying a set of quality cuts on the tracks reconstructed in the same event: we requested a certain degree of parallelism between the particles ($cos(\theta_{ij}) > 0.8$) and a reasonable quality of the tracks ($\chi^2 < 50$). Finally, in order to reduce the level of the spurious coincidences when correlating multi-track events from different telescopes, a cut on the number of tracks reconstructed per event in each telescope was applied ($n_{tracks} > 2$).

Figure 3 shows the distribution of the number of tracks per event reconstructed by the 39 EEE telescopes in operation during the period under investigation: even though the distribution follows a decreasing trend, the number of events with a large number of tracks per event is not negligible. However we can not exclude that a portion of events with higher multiplicity can be due to noise in the chambers.

Once the multi-track events were selected in each telescope, all possible pair combinations between the 39 telescopes were considered (741 in total). For each

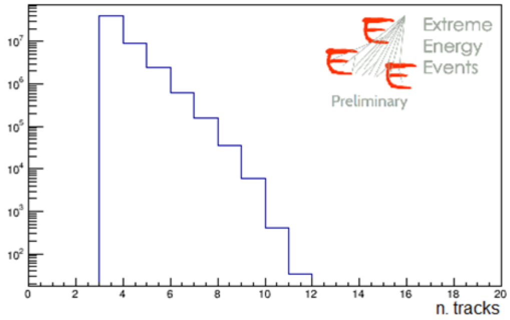

Figure 3: Distribution of the number of tracks per event reconstructed by the 39 telescopes included in the analysis.

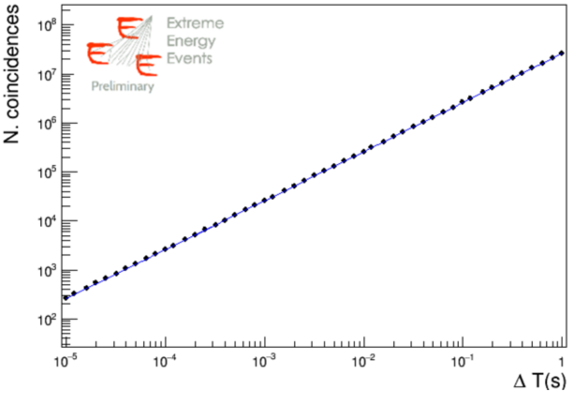

Figure 4: Number of coincident events (in black) as a function of the time window, compared with the expected number of accidental coincidences (blue line). The error bars due to statistical uncertainties are reported but are smaller than the size of the markers. A cut (d > 5 km) on the distance between the telescopes was applied to exclude true coincidences produced by two telescopes detecting the same EAS.

telescope pair we firstly selected those candidate events which stayed within a time window of 1 second. Such procedure resulted in the selection of about 50 million events. This dataset includes also coincidences between telescopes placed in the same town. Such events have to be excluded from the analysis since they are due to the detection of a single EAS by two close telescopes. Thus a cut on the relative distance between the telescopes was applied (d > 5 km). The possible existence of long distance correlations should be based on the observation of an excess of coincident events with respect to the background of spurious coincidences. For large correlation time windows (e.g. 1 s) the level of accidental background is predominant and no conclusion can be drawn. Moreover, all candidate events should stay within the time window dictated by the distance between the sites: for instance the largest distance covered by the telescope pairs of the EEE array corresponds to 5 ms. Thus the number of coincidences was estimated in smaller time windows and compared with the number of accidental coincidences as estimated by proportionally scaling the number of events measured in 1 second interval. Figure 4 shows the number of coincident events as a function of the time window for the selected multi-track events. The data points (in black) are compatible with the level of accidental background (blue line) within the statistical uncertainties. In such conditions no significant excess was observed.

This result can give rise to two possible interpretations: the level of accidental coincidences still dominates over the rare events of EAS correlations or the long distance correlations are not detected because they actually do not exist. In order to verify the first explanation, we tried to apply more selective cuts on the multitrack events. Even with a loose cut (i.e. $n_{tracks} > 3$) a small excess of events starts emerging over the accidental background. The most significant excess was observed selecting events with $n_{tracks} > 4$, the result is shown in Figure 5.

The excess starts to be visible for $\Delta T < 0.2$ ms, according to what expected from the constraints imposed by the telescope distances. In principle, this result can be improved applying a proper correction that takes into account the arrival time difference of the two showers, which depends on the inclination of their axis with respect to the vertical. Such correction would cancel the arrival time difference of correlated showers and would

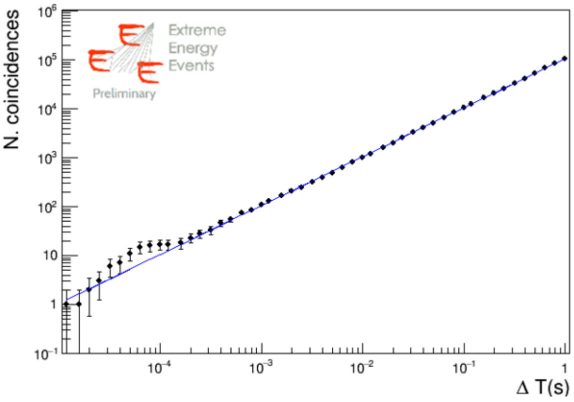

Figure 5: Number of coincident events (in black) as a function of the time window, compared with the expected number of accidental coincidences (blue line). The error bars due to statistical uncertainties are reported but are smaller than the size of the markers. With respect to Figure 4, a cut on the number of tracks per event ($n_{tracks} > 4$) was applied.

Event	EEE pairs	$n_{tracks1}$	$n_{tracks2}$	Distance (km)	$\theta_{rel}(deg)$	Date
(A)	CERN-BOLOGNA	7	5	456	21	January 2016
(B)	L'AQUILA-BOLOGNA	7	6	290	41	April 2016
(C)	CERN-CATANZARO	5	7	1194	18	May 2016
(D)	L'AQUILA-TORINO	5	5	551	23	May 2016
(E)	LODI-SAVONA	5	5	137	24	October 2016
(F)	FRASCATI-REGGIO EMILIA	5	5	361	71	December 2016
(G)	CAGLIARI-LODI	6	5	675	50	January 2017
(H)	CERN-PATERNÒ	5	5	1208	41	March 2017
(I)	BOLOGNA-CATANZARO	6	5	767	36	March 2017
(J)	L'AQUILA-LECCE	6	5	456	64	June 2017
(K)	BOLOGNA-SAVONA	5	5	229	24	October 2017

Table 2: List of candidate events observed within a time window $\Delta T \approx 60\ \mu s$. The columns report the site pair observing the event, the number of tracks in that event in the 2 telescopes, the relative distance between the sites, the relative angle between the showers and the date of occurrence.

narrow and shift to lower ΔT values the observed excess of events. However, due to the experimental uncertainties in the relative angle between the two showers, we are still investigating the actual possibility to apply such correction to our data [26].

The data in Figure 5 can be used to evaluate the coincidence event rate as a function of the time interval ΔT, that is shown in Figure 6. The average rate due to accidental coincidences between the telescopes is expected to be of the order of 10^5 coincidences in a time window of 1 second (blue line). However the data show a small deviation from that value in correspondence of $\Delta T \approx 10^{-4} s$.

For each time interval ΔT, we evaluated the p-value (according to Poisson distribution) to obtain by chance a number of events greater or equal to the number of events experimentally observed in that ΔT, supposing that the number of expected events is obtained by proportionally scaling the number of events measured in 1 second. The most significant p-value was obtained for $\Delta T \approx 60\ \mu s$ and is equal to 4×10^{-3}. Within such time window, 11 events were observed against ~5 expected events due to accidental coincidences. The list of these 11 events, with their main properties, is reported in Table 2.

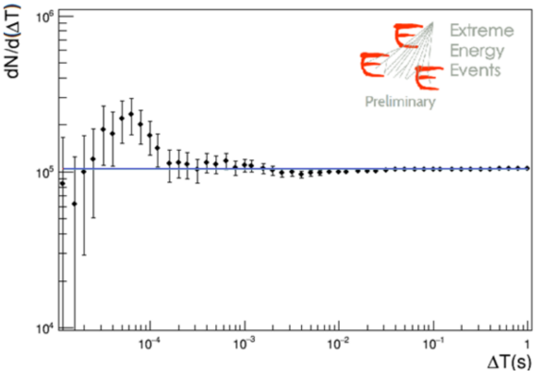

Figure 6: Number of coincident events $dN/d(\Delta T)$ between all 741 pair combinations of the 39 EEE telescopes involved in the analysis. The blue line indicates the average rate expected in case of accidental coincidences.

The 11 events seem to be randomly distributed in terms of location of the sites involved and time of occurrence. The number of tracks per event are 6 on average, hence far from the upper tail of multiplicity distribution shown in Figure 3. It is worth mentioning that half of these events are characterized by a value of the relative angle between the showers lower than 25°, suggesting a possible angular correlation between the showers, as expected by the production mechanisms. However in-depth studies of the topology of such events is still ongoing, together with an investigation of the criteria adopted for the selection of the multi-track events.

4. Conclusions and outlook

After more than 10 years of data taking, the EEE experiment started looking at coincident and parallel EAS pairs between distant sites. Different analysis approaches have been considered, in order to cope with the undesired background of spurious coincidences. The results from two different analyses have been presented, the first based on the correlation between the 10 EEE telescope clusters and the second on the multi-track events correlation between all the telescopes of the network.

Both analyses lead to the extraction of few candidate events which are characterized by small values of the time difference and in some cases also by a small angular difference between EAS orientations. However no definitive conclusion can been drawn since higher statistics is needed to improve the significance. In this respect the ongoing upgrade of the EEE array will answer this need shortly. Finally, some aspects of this analysis are still under investigation, especially for what concerns the selection of the multi-track events and the correction for the arrival time difference of the showers in the detection sites.

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