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Società Italiana di Fisica

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Regular Article

Search for long distance correlations between extensive air showers detected by the EEE network

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Abstract. A search for long distance correlations between individual Extensive Air Showers (EAS) detected by pairs of MRPC telescopes of the Extreme Energy Events (EEE) network was carried out. The search for an anomaly in these events is the purpose of our work. A dataset obtained by all the possible 45 pairs between 10 EEE cluster sites (hosting at least two telescopes), located at relative distances between 86 and 1200 km, was analyzed, corresponding to an overall period of 3968 days time exposure. To estimate the possible event excess with respect to the spurious rate, the number of coincidence events was extracted as a function of the time difference between the arrival of the showers in the two sites, from ± 10 s to the smallest time interval where events are still observed. The analysis was done taking into account both the time and orientation correlation between the showers detected by the telescope pairs. A few candidate events with unusually small time difference and angular distance were observed, with a p-value sensibly smaller than a confidence level of 0.05.

1 Introduction

The development of an Extensive Air Shower (EAS) in the Earth atmosphere is caused by a high-energy primary particle (in most cases a proton), which may produce thousands or even millions of secondary particles, due to the complex interactions which take place in the atmosphere. A large part of the most penetrating components in the shower are muons, which are able to arrive at the sea level. The time and orientation correlation between several muons originating from the same shower is employed to reconstruct the main properties of the primary particle (energy, arrival orientation) by coincidence measurements between detectors located within the area covered by the shower itself.

The possibility to observe cosmic rays time correlations between detectors separated by distances much larger than the extension of the highest-energy EAS (a few km) has been long discussed over the years. Possible physical mechanisms which could justify the existence of such events have been proposed [1–10].

Our purpose is the search for any possible anomaly in the observed events. The physics motivation for the existence of an anomaly is the following. At extreme energies nobody knows how many phase transitions can be involved in the evolution of the Universe. In fact, the higher the energy, the more complex the interacting system of particles whose fundamental nature is unknown. For example, the so-called Quark Gluon Coloured World (QGCW) must exist before QCD (which gives rise to our quark-gluon zero colour world). All we know is that from the extreme energies, via phase transitions, should derive all known interactions (QCD, QFD, QED) and particles (quarks and leptons of three families). The evolution of the Universe has gone through a series of phase transitions whose last step is at the Fermi energy where $\mathrm{SU}(2) \times \mathrm{U}(1)$ generate QED and QFD. This is the low energy level.

At even higher energies, there are the energy level E_{GUT} ($\sim 10^{16}\,\mathrm{GeV}$) where the three gauge couplings ($\alpha_1, \alpha_2, \alpha_3$) converge [11] and the energy level E_{SU} ($\sim 10^{18}\,\mathrm{GeV}$) where the Relativistic Quantum String Theory (RQST) puts the origin of the gravitational force. The gap [12,13] between E_{GUT} and E_{SU} could indeed be another source of phase transition. In addition we should not forget that E_{SU} has as bias the Planck energy level ($E_{\mathrm{Planck}} \sim 10^{19}\,\mathrm{GeV}$). This telegraphic synthesis tells us that the study of the highest-energy cosmic rays could be the only source of information about these unknown phase transitions. Purpose of the Extreme Energy Events network is the search for any possible anomaly in the observed events.

The Extreme Energy Events (EEE) network [14,15], based on Multigap Resistive Plate Chambers (MRPC) telescopes, allows to detect with high efficiency cosmic muons and reconstruct their arrival direction with optimal angular resolution. The wide coverage of a large territory (hence the availability of detectors spanning a large range of distances), the number of its sites and the large overall time exposure due to the continuous data taking of its stations is a unique property of our experimental setup.

The number of EEE telescopes taking data is presently 53, and a few EEE sites are also equipped with two or three telescopes located in the same metropolitan area, thus allowing to observe coincident events originating from extensive air showers developing over an area of a few km^2. At present 10 EEE sites have observed evidence of extensive air showers of various primary energies, depending on the distance between the telescopes, which can be as low as 15 m at CERN or very high (about 3000 m) in the Catania site. While the coincidence rates between two distant individual telescopes (each taking data with a single rate of 10–50 Hz) are largely dominated by spurious events, these are strongly reduced when coincidences are considered between telescope pairs, each detecting extensive air showers with a reasonable signal-to-noise ratio.

Other experimental searches, with smaller detector networks, are available from the LAAS [16–18] and CZELTA-ALTA [19,20] Collaborations. Current rate expectations range from 10^{-3} to 1 event per km^2 per year (see also possible estimates from [1–10]).

In this paper we report the preliminary results of an investigation carried out on a large dataset obtained by means of the MRPC telescopes of the EEE network, searching for long distance, time and orientation correlations between independent EAS as detected by telescope pairs. Section 2 is devoted to discussing the peculiarities of the EEE project, the detector performance, the experimental setup and data taking conditions. Section 3 discusses the method and possible strategies to be employed to search for long distance correlations between sparse detectors. Section 4 reports the experimental results of the present analysis, which spans an overall data taking period corresponding to more than 10 years. Some conclusions and future prospects are reported in sect. 5.

2 The experimental setup and running conditions

2.1 The EEE project

The EEE project is a joint educational and scientific initiative by Centro Fermi (Enrico Fermi Historical Museum of Physics and Research and Study Centre) [14,15] in collaboration with INFN (Italian National Institute for Nuclear Physics), CERN and MIUR (the Italian Ministry of Education, University and Research). The project has built and installed an array of cosmic ray detectors, distributed in several sites, spanning all the Italian territory, over an area larger than $3 \times 10^5\,\mathrm{km}^2$ (see fig. 1). Several cluster sites host two or more telescopes in the same metropolitan area, as shown by red (or orange) dots close to each other.

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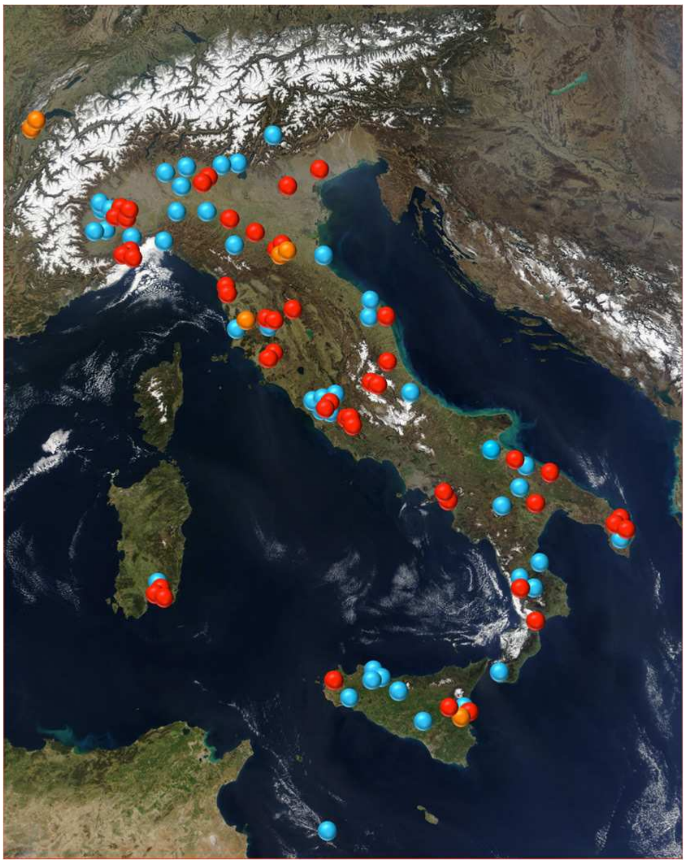

Fig. 1. Map of the EEE telescopes. The red dots mark the geographical locations where a telescope is located. Orange dots locate the EEE telescopes operating in INFN/Physics Departments sites. In a few towns more than one telescope is installed. Finally, blue dots point out the locations where additional schools are participating in the EEE project, without hosting a telescope.

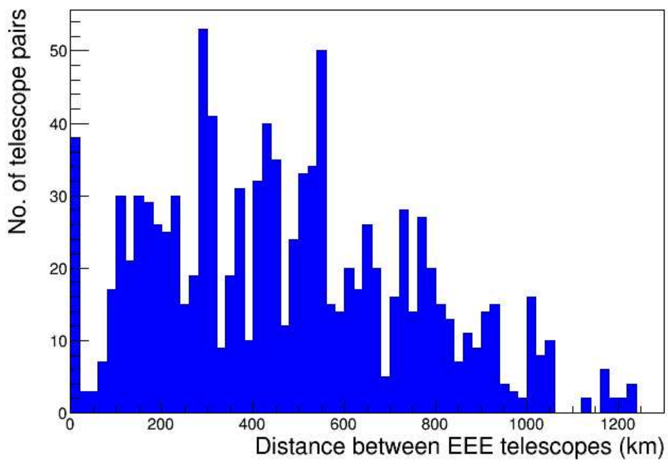

Fig. 2. Distribution of the distances between telescopes in the EEE network. A bin size of 20 km was assumed in the histogram. The first bin includes all the telescope pairs located in the same metropolitan area, at relative distances up to about 3 km.

The distances between any telescope pair in the array vary between very small values (15 m) and over 1200 km. Figure 2 shows the distribution of these distances, arranged with a bin size of 20 km. The entries in the first bin (relative distances between 15 m and a few km) refer to the telescopes (two or more) located in the same metropolitan area, which are mainly used to detect local extensive air showers of various energies depending on the distance between the telescopes. An optimal air shower identification and reconstruction needs the combined information from several telescopes. Presently, only a few geographical sites are equipped with more than two telescopes.

We plan to also measure, in the near future, n-fold coincidences ($n > 2$) between those telescopes located in the same town at reasonable relative distances, although the expected rate for these events is very low.

Concerning the telescope pairs located in different towns, the EEE network covers a wide range of distances, which is an important aspect in this investigation, since no reliable prediction exists concerning the separation distance where correlated showers may be expected.

The research goals of the project include the study of the properties of the local muon flux and its dependence on planetary and solar environment, the detection of high-energy extensive air showers created in the Earth atmosphere by time and orientation correlations between two or more telescopes, and the search for possible long distance correlations between far telescopes. Other physics items of interest also include the study of the upward muon flux and the search for small anisotropies in the equatorial coordinate sky map.

A powerful impact on education is also envisaged by the EEE project, which has already contributed to introducing a large number of school teachers and students (in the order of 1000 so far) to the problems and results of particle and astroparticle physics, by their direct involvement in an advanced research project.

Several results from the EEE project have already been reported [21–38]. Presently, 53 telescopes are actively taking data since several years. After a three weeks Pilot Run at the end of 2014, which resulted in a number of collected events of the order of 10^9, RUN1 was organized in 2015, with 35 telescopes on average participating in the data taking during a two months period, and an overall number of collected events close to 5×10^9. A second coordinated run (RUN2) lasted from October 2015 to May 2016, with 40 telescopes involved and 1.5×10^{10} events collected. In the present analysis combined data from RUN1 and RUN2 were considered. The data taking, RUN3, started in October 2016, approximately doubling the statistics collected so far, with an overall number of 50 telescopes participating in the data taking, and an average fraction of 70% active at the same time.

2.2 The MRPC telescopes and their performance

The detection technique employed by the EEE telescopes is based on three Multigap Resistive Plate Chambers (MRPCs), which provide the impact coordinates of each incoming muon, hence the reconstruction of its track, with a high efficiency and good angular resolution. Details on the construction of the MRPCs can be found in [15,21]. These detectors are based on the design of the MRPCs developed for the TOF detector [39,40] of the ALICE experiment at CERN LHC [41,42].

Each MRPC, built at CERN by high school teams under the supervision of researchers and technicians, has an active area $0.82 \times 1.58\,\mathrm{m}^2$. Typical distances between the chambers are about 50 cm. Each chamber has six gas gaps obtained by means of a sandwich of glass plates spaced by $300\,\mu$m. A continuous gas flow with a mixture of $C_2H_2F_4$ (98%) and SF_6 (2%) in the chambers is provided by a gas mixing station. The high voltage applied to the outer glass plates, up to ± 10 kV, generates a uniform electric field between the glass electrodes. Each MRPC is equipped with 24 copper strips (160 cm long, with a pitch of 3.2 cm) as signal pick-up electrodes, on both anode and cathode. A six-fold coincidence of the left and right front-end cards of the three MRPCs generates the data acquisition trigger.

The particle impact point on each MRPC plane is reconstructed by the hit strips —in one direction— and by the time difference in the arrival of signals at each strip end in the other direction, with a spatial resolution of about 0.7 cm for both coordinates. Adjacent hits contribute to define a cluster, by the average of their X- and Y-positions. Due to the spatial resolution, it is possible to estimate, through geometrical simulations, that the direction of particles crossing the EEE telescopes is reconstructed with a resolution of about 0.9°.

To tag each event, for the purpose of combining the information collected by different telescopes, the absolute time of each event is recorded with a GPS unit, with a precision in the order of a few tens of nanoseconds.

2.3 Data storage, monitoring and analysis

The combined overall acquisition rate of all the telescopes in the EEE project is now of the order of a few kHz, for a large part of the whole year. Since the amount of data collected by all the telescopes participating in the project is increasing each year, reaching roughly 20 Gbytes per day, the storage, pre-processing, data monitoring and general access to the data collected for further physics analyses was a point of concern for the whole EEE Collaboration. For this reason, the EEE project joined the INFN CNAF cloud facility to create its own data collection centre. The CNAF cloud provides a flexible environment based on OpenStack and virtualization, which allows to allocate, on demand, resources adapted to the need of the experiment and to collect data from the telescopes distributed in a wide territory. During coordinated runs all the schools have been connected/authenticated at CNAF in order to automatically transfer data using a BitTorrent technology. Such procedure has been recently updated for the ongoing RUN3.

Together with this storage service, the EEE experiment exploits the CPU resources of the CNAF centre by running an automatic data processing procedure for the reconstruction of the tracks. After processing the raw data, several quality plots are made available on the web page devoted to EEE monitoring. Moreover, an automated monitoring procedure is running [43], which produces a daily report describing the current status of all the telescopes participating in the coordinated run.

3 Correlation analysis strategy

To search for possible long distance correlations between cosmic rays, different strategies may be adopted, in order to handle the huge amount of spurious coincidence events between detectors and enhance the probability of observation of rare events. These are listed below, with some numerical estimates of the detection of single and coincidence rates involved.

3.1 Correlation between independent telescopes

The count rate of each individual EEE telescope is of the order of 10–50 Hz, depending upon several factors, which may be different from site to site. One factor is the distance between the detection planes, which for most of the telescopes is fixed at 50 cm, but for some telescopes, due to mechanical constraints, is larger (up to 80 cm). Since the trigger is given by the six-fold coincidences between the left and right front-end signals (see sect. 2.2), the overall efficiency is at least proportional to the third power of the individual MRPC efficiency (in most cases the left and right signals are not independent). Another important factor is the amount of shielding which a muon must traverse before arriving to the detector, which sometimes is located at the ground floor (or even underground) in a building with several floors. We evaluated that the muon momentum threshold to traverse several concrete slabs may amount up to several hundred MeV/c, thus reducing the muon flux by a non-negligible amount. Also the altitude of the site above sea level influences the observed trigger rate.

After imposing quality cuts on the reconstructed muon tracks, which slightly reduces the rate of good events, the actual rate of good muon tracks is still of several tens of Hz. With an assumed average value of 20 Hz for single muons detected in each telescope, and taking as a reference a time window of 1 ms (corresponding to the typical value of the separation in the arrival times of particles roughly moving at the speed of light for telescopes located hundreds km apart), the estimate of the spurious coincidence rate in this case amounts to $2 \times 20 \times 20 \times 10^{-3} = 0.8\,\mathrm{Hz}$. With a spurious rate of about 1 Hz, one may expect an order of 10^5 spurious events per day between any two telescopes, which is many orders of magnitude beyond any optimistic estimate of physics events to be searched for.

The reconstruction of the muon orientation in each telescope gives the possibility to select muon tracks with a certain degree of parallelism, thus reducing the rate of spurious events in comparison to that of physics events. This is the strategy which is commonly adopted when searching for correlations between muons belonging to the same extensive air shower, since it is known that muons in a shower are emitted within a narrow cone around the direction of the primary. In the case of the EEE telescopes, located at short relative distances (less than 3 km), able to detect coincident muons from the same shower, selecting tracks with an angular difference smaller than about 20° results in a decrease of about one order of magnitude in the spurious coincidence rate, while preserving most of the correlated muons. The same strategy applied to the correlation between distant detectors is not however selective enough to reduce the random rate, so that still a number of 10^3–10^4 random events per day would be observed, thus excluding the possibility to observe any real physics event.

3.2 Correlation between a single muon and a two-track event in another telescope

Due to the area of each EEE telescope, in a small fraction of the events even two correlated particles may be detected and tracked. In some cases, these are two independent muons belonging to the same shower, while sometimes the two particles originate from nuclear interactions of a single particle in the building surrounding the detector or even from electrons originating from the muon decay in the ground. The rate of two track events —irrespective of their origin— is of the order of 10^{-3} with respect to the single track rate, say for instance 0.02 Hz for a single rate of 20 Hz as assumed before. In such case, the spurious counting in 1 ms time window amounts to $2 \times 20 \times 0.02 \times 10^{-3} = 8 \times 10^{-4}\,\mathrm{Hz}$, corresponding to about 100 events per day, which is still very high.

3.3 Correlation between two-track events in both telescopes

If two track events are selected in both telescopes, with individual rates of about 0.02 Hz, the rate of spurious counting may be estimated in these conditions as $2 \times 0.02 \times 0.02 \times 10^{-3} = 8 \times 10^{-7}\,\mathrm{Hz}$, corresponding to about 0.07 events per day. Provided that a non-negligible fraction of the two track events comes from true muons belonging to the same shower, this strategy could be exploited.

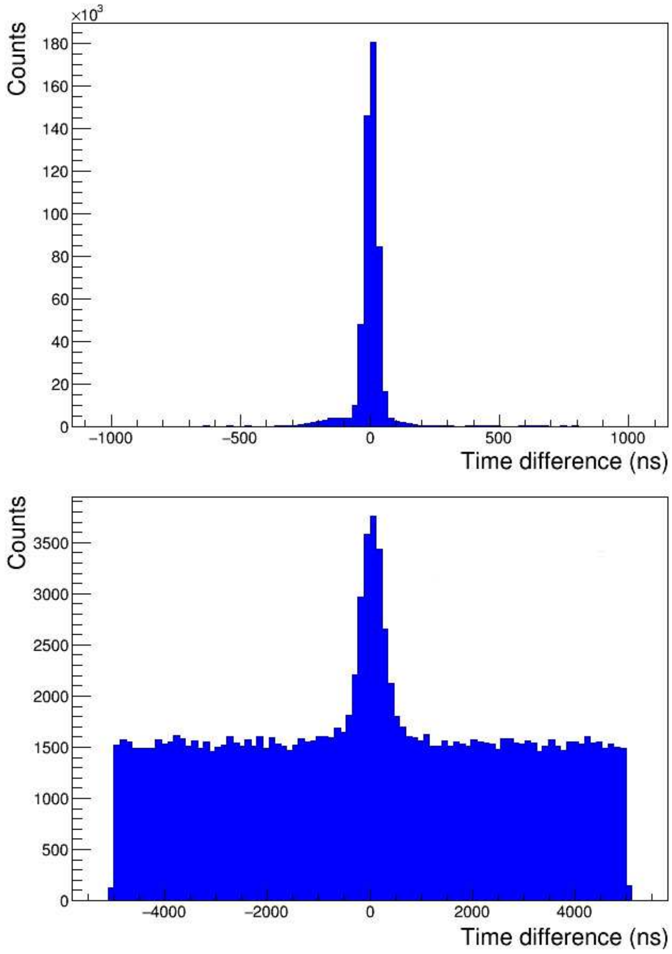

Fig. 3. Distribution of the time difference between the muons detected by the two telescopes located in the CERN site, at a distance of about 15 m (top) and in L'Aquila site, at a distance of about 200 m (bottom).

3.4 Correlation between telescope pairs (extensive air showers)

Taking into account the presence of at least two telescopes in the same area, at relative distances within a few km, hence able to detect extensive air showers from the time and orientation correlations between two independent muons, a better strategy would be to search for correlations between two telescope pairs. The coincidence rate of each telescope pair and the signal-to-noise ratio strongly depend on the relative distance between the two telescopes in the pair, and on the amount of spurious counting between them. As an example, fig. 3 shows two different situations, for the two telescopes located at CERN and in L'Aquila. In both cases, a loose cut on the relative angle between the two muons ($\vartheta_{\rm rel} < 40^\circ$) was introduced. The top plot shows the time difference between the arrival of the particles detected by the two telescopes located in the CERN site, very close to each other (only about 15 m distance). In this condition, extensive air showers are well identified, and a high coincidence rate between muons detected in the two telescopes is observed of the order of 0.04 Hz (corresponding to several thousand air showers per day). The bottom plot shows the same quantity for the two telescopes located in L'Aquila site, at a relative distance of about 200 m. Whereas the time coincidence peak is clearly visible, a non-negligible amount of spurious coincidences is observed below and on the two sides of the main peak. The signal-to-noise ratio becomes worse with increasing the distance between telescopes in the pair, so that for large relative distances the time peak is hardly visible on the spurious background. It must be pointed out however that even in the worst cases —due to the purity of the muon samples in each detector— the coincidence rate between the two telescopes is always originated from two cosmic muons which likely belong to two independent showers detected within the coincidence time window.

Concerning the estimate of the counting rate in such conditions, the frequency of detection of extensive air showers (or better the observed frequency of two muons seen by any two telescopes located in the same town) varies between 0.001 and 0.04 Hz. The corresponding frequency of spurious coincidences varies correspondingly between wide limits. For instance, assuming a rate of 0.04 Hz for the CERN site and a rate of 0.001 Hz for another site, the spurious expected rate is $2 \times 0.04 \times 0.001 \times 10^{-3} = 8 \times 10^{-8}$ Hz, corresponding to about 7×10^{-3} events per day, or one event in about 150 days of data taking.

Table 1. Distance between cluster sites (km). The labels identifying the various sites refer to the geographical locations of Bologna (BOLO), Cagliari (CAGL), Catania (CATA), CERN, Frascati (FRAS), Grosseto (GROS), L'Aquila (LAQU), Savona (SAVO), Torino (TORI), Viareggio (VIAR). The minimum and maximum values of the distance between telescope pairs is marked in bold.

	BOLO	CAGL	CATA	CERN	FRAS	GROS	LAQU	SAVO	TORI	VIAR
BOLO	–	614	835	450	317	195	290	230	296	114
CAGL		–	552	817	413	426	501	566	659	522
CATA			–	**1200**	517	670	555	934	1040	816
CERN				–	725	560	720	285	180	425
FRAS					–	165	**86**	439	542	302
GROS						–	193	274	377	142
LAQU							–	453	550	307
SAVO								–	105	149
TORI									–	244
VIAR										–

Possible mechanisms [1–10] have been proposed involving single sources that could emit two correlated particles or nuclei producing, in turn, two correlated extensive air showers in the Earth atmosphere, in particular the so-called Gerasimova-Zatsepin (GZ) mechanism, which invokes the photodisintegration of a primary heavy nucleus in two lighter but highly energetic fragments by interaction with a solar photon. The strategy used in this analysis, *i.e.* the search for anomalies looking for correlations between two individual distant EAS, does not exclude any of the above ideas.

Presently, the EEE network includes 10 sites with at least two telescopes located at relative distances allowing for the detection of extensive air showers. In this analysis it was then decided to employ this strategy, looking for possible candidate events originating from time and orientation coincidences between telescope pairs located in these sites (four-fold telescope coincidences).

The study of two correlated air showers does not automatically select very high-energy showers, which should be identified by their extended lateral profile, as is common practice for large arrays. The flexibility of the EEE network could somewhat contribute in the future to detect correlations, if any, at distances larger than the usual size of a high-energy shower (a few km). Apart from the telescope pairs located within a distance compatible with the lateral profile of a high-energy shower, there are presently 42 EEE telescope pairs with relative distance between 5 km and 100 km, and this number will hopefully increase in the future.

4 Experimental results and discussion

In the present analysis a dataset of events originating from 10 EEE sites, each equipped with two MRPC telescopes, was considered. The distances between the sites which include at least two telescopes range between 86 km and 1200 km, as shown in table 1, which reports these values for all 45 combinations. To search for long distance correlations between extensive air showers, it is required that each of the four telescopes involved in the combination (two per site) is active. Depending on the individual duty cycle of each telescope, the common live time between any two sites was estimated and reported in table 2, rounded to an integer number of days. As is shown, these values range from 16 days to more than 320 days. Although including a wide range of distances, the sum of all the periods involving two different cluster sites results in an overall time exposure of nearly 4000 days (about 11 years).

For each site, a shower was selected by a proper time cut around the coincidence peak (fig. 3), from a few hundred ns to about 1 μs, depending on the distance between the two telescopes in the pair, and also imposing a loose cut on the relative angle between the two muons ($\vartheta_{\rm rel} < 40°$), to slightly enhance the signal-to-noise ratio.

A preliminary correlation analysis between distant sites was done by a time scan of the events, as a function of the time difference $\Delta t = |t_1 - t_2|$ between the arrival of the showers in the two sites. The number of coincident events, $dN/d(\Delta t)$ between any two sites was extracted, from $\Delta t = \pm 10$ s down to the smallest value where events are still observed. As an example, fig. 4 shows the result obtained for the correlation between the CERN and Cagliari sites. The value observed for large Δt gives the estimate of the expected number of spurious events when extrapolated to small time differences. Any excess with respect to this should appear for small Δt, of the order of ms, compatible with the distance between the two sites (817 km). As is seen, no evidence of significant enhancement in the quantity $dN/d(\Delta t)$ is observed from such plot for Δt around a few ms.

Table 2. Common measure time between EEE cluster sites (rounded to integer days). An overall data taking period of about 3968 days was exploited with the present dataset.

	BOLO	CAGL	CATA	CERN	FRAS	GROS	LAQU	SAVO	TORI	VIAR
BOLO	–	155	80	95	73	52	70	118	104	105
CAGL		–	108	126	102	54	101	326	154	154
CATA			–	75	56	24	61	99	93	93
CERN				–	66	27	67	109	86	123
FRAS					–	16	41	91	72	87
GROS						–	31	30	30	18
LAQU							–	75	67	68
SAVO								–	130	143
TORI									–	118
VIAR										–

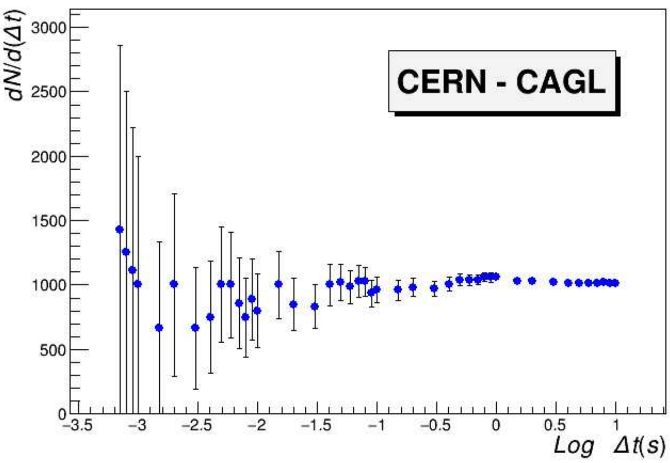

Fig. 4. Number of coincident events $\mathrm{d}N/\mathrm{d}(\Delta t)$ between the two clusters located at CERN and in the Cagliari site as a function of the logarithm of the time difference Δt between the arrival of the showers in the two sites, from $\Delta t = 10\,\mathrm{s}$ down to less than 1 ms.

The same analysis was carried out for all the site pairs in table 1. Introducing a cut on the relative angle between the two showers —as estimated by an average of the directions of muons detected by the two telescopes in each site— gives a strong reduction of the spurious counting; if true correlated showers have small relative angles a better signal-to-noise ratio could be obtained, thus evidencing any small excess. For such reason a similar analysis was also exploited for different values of such cut, from 10° to 40°, considering that a large uncertainty is associated to the angular difference between the two showers. It is worth stressing that a non-negligible contribution (a few degrees) to the angular difference in the muon arrival directions also originates from the different location (longitude and latitude) of the sites, due to the Earth's curvature. As an example, with a reasonable cut $\vartheta < 20°$, we observed in a few cases a small enhancement for Δt of the order of a few ms, as shown in fig. 5, for the correlation between the CERN site and all the other EEE cluster sites. However, due to statistics, such enhancement is in most cases compatible with the null hypothesis. Moreover, in other cases, a negative effect is seen, which is still compatible with statistical fluctuations. Errors in figs. 4 and 5 are only statistical and bin-to-bin correlated, since the statistics in each left-most bin is included in the right adjacent bin.

Another strategy is then to search for candidate events which have a time difference within the value dictated by the distance between the sites. Such value was estimated by $(d/c) \times \sin(\vartheta_m)$, where d is the distance between the sites and ϑ_m is an estimate of the maximum value of the zenith angle —with respect to the vertical— under which muons from two correlated shower may still be detected in the telescopes. A reasonable value $\vartheta_m = 50°$ was assumed. For each event, we evaluated the corresponding p-value (according to Poisson distribution) to obtain by chance such an event, considering the number of expected events in a time window equal to the measured time difference $|t_1 - t_2|$ and with a relative angle between the two showers not exceeding the actual observed value of ϑ_{rel}.

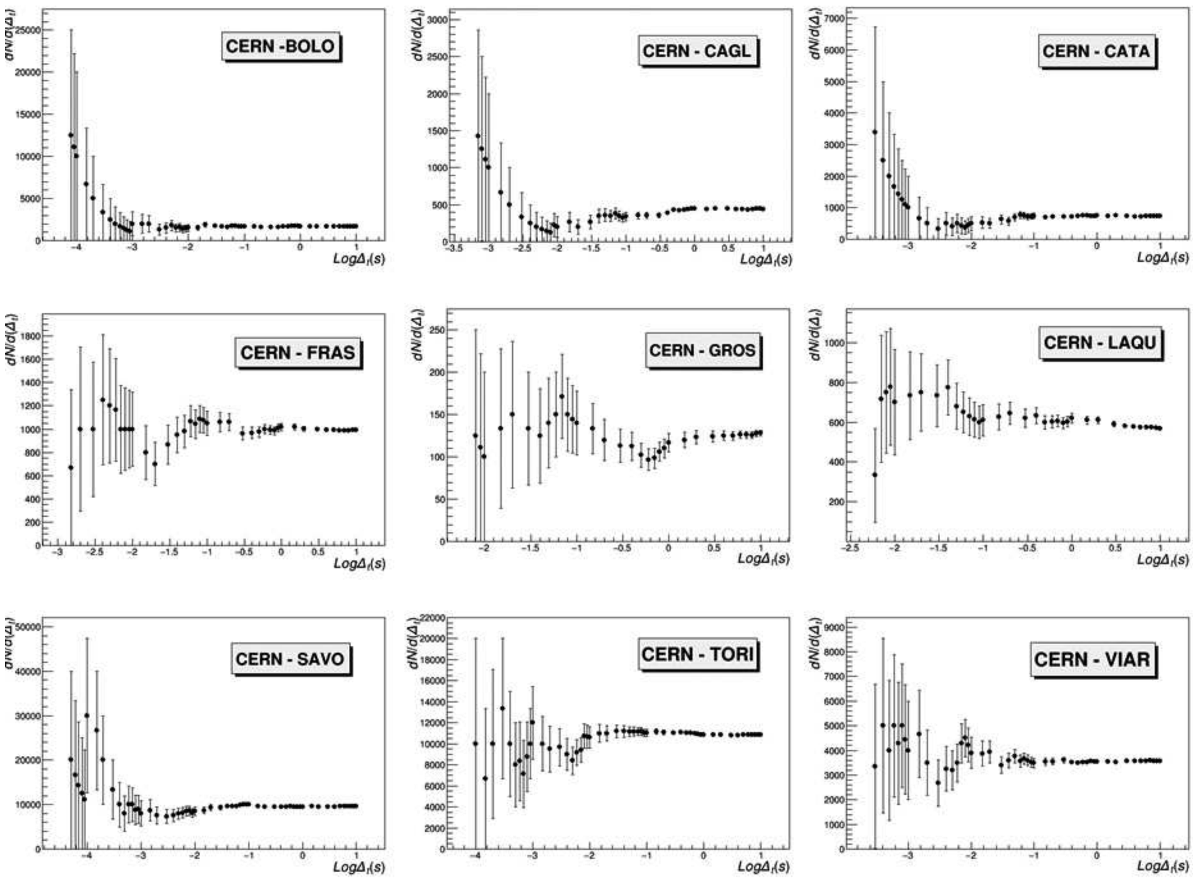

Fig. 5. Number of coincident events $\mathrm{d}N/\mathrm{d}(\Delta t)$ between the CERN site and the other EEE sites, with a cut on the relative angle between the two showers, $\vartheta_{\mathrm{rel}} < 20^{\circ}$.

Table 3. List of the most significant candidate events observed within a time window compatible with the distance between the sites (see text). The second column reports the site pair for which the event was observed, while the relative distance between the sites is reported in column three. The other colums show the time difference between the arrival of the showers in the two sites $|t_1 - t_2|$ (in μs), the relative angle between the showers, the expected number of spurious events in $|t_1 - t_2|$ and the corresponding p-value. Events (A) to (E) have been selected on the basis of a p-value smaller than 0.05. Events (F) to (L) are five additional events found in increasing order of p-value.

Event	EEE pairs	Distance (km)	$\lvert t_1 - t_2\rvert$ (μs)	ϑ_{rel} (deg)	Expected events	p-value	UTC time
(A)	BOLO-CAGL	614	86	27.1	0.0069 ± 0.0002	0.007	26.11.2015 19 h 07′ 16″
(B)	BOLO-LAQU	290	740	9.1	0.014 ± 0.001	0.014	25.03.2016 18 h 31′ 05″
(C)	CATA-TORI	1040	88	9.2	0.0265 ± 0.0005	0.026	09.01.2016 06 h 42′ 15″
(D)	GROS-TORI	377	297	14.4	0.032 ± 0.001	0.031	04.06.2016 02 h 31′ 08″
(E)	CERN-CATA	1200	248	9.3	0.049 ± 0.001	0.048	15.02.2016 01 h 28′ 29″
(F)	CAGL-CERN	817	690	8.7	0.073 ± 0.002	0.070	26.02.2016 09 h 21′ 58″
(G)	CERN-SAVO	285	99	6.1	0.108 ± 0.001	0.102	24.11.2015 12 h 35′ 47″
(H)	CAGL-SAVO	566	99	19.9	0.115 ± 0.001	0.109	08.04.2015 00 h 02′ 50″
(I)	BOLO-CERN	450	73	19.4	0.1194 ± 0.0001	0.112	03.05.2016 06 h 46′ 35″
(L)	LAQU-SAVO	453	760	10.9	0.142 ± 0.003	0.132	13.12.2015 21 h 43′ 00″

This analysis resulted in a number of candidate events for which the p-value is relatively low, given the time difference $|t_1 - t_2|$, the relative angle and the number of expected spurious events in that interval. Such events are reported in table 3, with their main properties (time difference, relative angle between the two showers and UTC time, together with their p-value). Five events ((A)–(E)) have a remarkable p-value smaller than 0.05. For some events ((A), (C)) the time difference is smaller than 100 μs, and three events have a relative angular distance smaller than 10°.

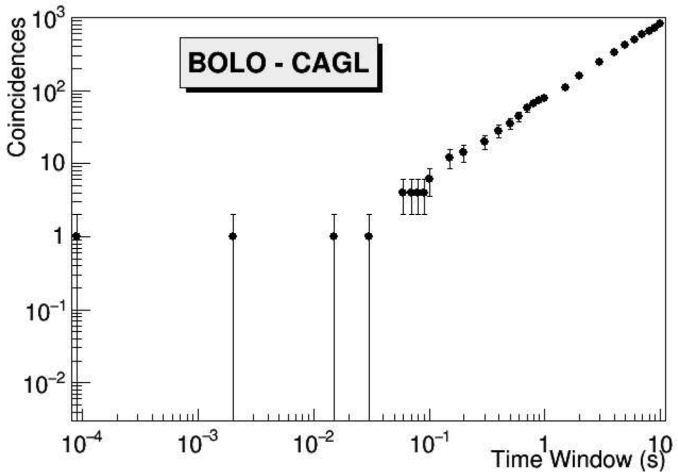

Fig. 6. Number of coincident events as a function of the time window, with an angular cut corresponding to the value observed for the event (A) reported in table 3.

The uncertainty in the relative angle between the two showers depends on several factors contributing to determine the uncertainty in the direction of each individual shower. This in turn depends on the zenith angles ϑ_1, ϑ_2 (which have a small uncertainty, of the order of $1°$), on the azimuthal φ_1, φ_2 angles of the two muons reconstructed by the two telescopes, and on the geographical relative orientation of the two telescopes, which has a larger uncertainty, of the order of a few degrees. Moreover, also the intrinsic uncertainty associated to the direction of the primary particle when estimated by the average direction of only two muons in the shower is an important factor, which amounts to a few degrees. For such reason, apart from the most significant events ((A)–(E)), a few additional events were considered, for which the probability is slightly larger than the assumed confidence level (events (F)–(L)), although with a small value either of time difference or of relative angle.

Since the axes of the two showers are not exactly parallel to each other, a large uncertainty is associated to the correction in the arrival time difference. Taking into account, by a simulation, the convolution of the different uncertainties, it was verified that for most of the events in table 3 (7 out of 10) the observed difference in the arrival time between the two showers is compatible with their relative direction, while in a few cases (events (B), (D) and (L)) this is not the case. This could simply mean that either these events result from random coincidences, or the correction cannot be based on the simple assumption that the two showers travel with parallel wave fronts. Actually, possible mechanisms, if any, which could justify long distance correlations between cosmic rays, do not necessarily imply small relative angles between the two showers (even though this is a reasonable picture), so that their correlation in time could be more meaningful than a close correlation between their incoming directions.

As a further check of the significance of the observed result, a time correlation between the events measured in distant sites was studied by introducing a shift of an amount Δ in the time difference and searching for correlated events within the same time window as for the observed event of interest. The quantity Δ was varied between 10 ms and 10 s, in steps of 10 ms, for a total number of 1000 trials. It was verified that the average number of spurious events over these 1000 time windows was compatible within statistics with that reported in table 3, according to the meaning of p-value.

For the events reported in table 3, the trend of the spurious number of events as a function of Δt, with the actual value of the relative angle between the two showers taken into account, may be analyzed. As an example, one of such results is shown in fig. 6. In the plot, the event of interest has the smallest value of Δt, and its occurrence may be compared with the observed trend of the spurious rate, as inferred by the values measured for large values of Δt.

Concerning an overall significance of these events, it must be noted that the p-values in table 3 represent the probability that each particular event might be accidental, as estimated by considering the rates in that particular pair of clusters. The significance level of the measurement depends on the overall behaviour of the system, *i.e.* can differ significantly, depending on the fact that other pairs of clusters have observed low p-values events or not. As a first consideration about the overall significance, we can note that out of 45 site combinations, no events were observed for 20 site combinations within the time difference compatible with their mutual distance, while at least one event was observed in 25 site combinations.

The possibility of combining the information from all the observed events into a single quantity, giving an overall significance of the measurements is certainly attractive; however this is not quite easy, since the events refer to different station pairs, located at very different relative distances and with different relative orientations between the showers. Since the evaluation of the background contribution is strictly related to the values of the time difference and of the relative angle, this contribution needs to be calculated for each individual event observed. A rough attempt to get some global feature concerned with all the station pairs was to consider only the most significant event, if it exists within the

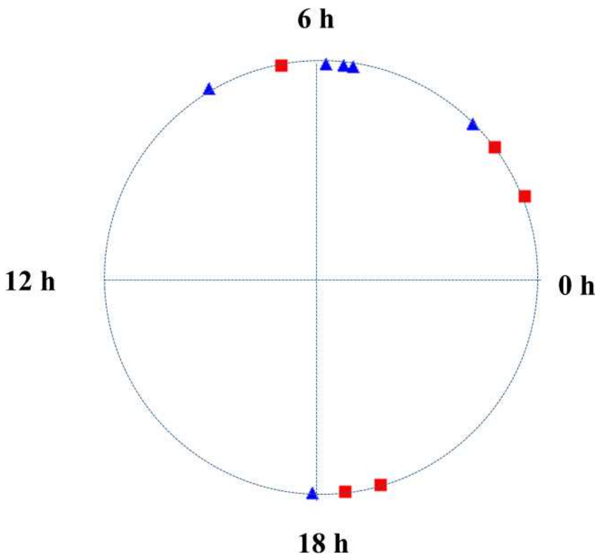

Fig. 7. Distribution of the most significant observed events along the local daytime, plotted as red squares in the figure. Also plotted are the six events reported by the LAAS Collaboration [16], as blue triangles.

correct time window, for each site pair (25 events) and compare this quantity to the corresponding number of expected event (6.79 events). This comparison largely underestimates the background and may be misleading, since for several station pairs more than one event was observed, while for other pairs no event was found. A more realistic approach would be to consider all the observed events (each with its $|t_1 - t_2|$ and $\vartheta_{\rm rel}$) within the correct time window. For those station pairs where more than one event is observed, the background was estimated considering the largest values of $|t_1 - t_2|$ and $\vartheta_{\rm rel}$. Finally, for the station pairs where no events are found, the background was estimated considering the overall time interval determined by the mutual distance between the stations, $(d/c) \times \sin(\vartheta_m)$, as specified before, and any possibile relative orientation between the two showers ($\vartheta_{\rm rel} < 180°$). With this method, we have 96 events arising from all 45 combinations, with an expected number of events equal to 77.8, roughly corresponding to a 2σ effect. Once again, one has to remember that considering together events which were measured under different relative distances is not without ambiguity. This means that on a global scale, the observed number of events between all site pairs could be compatible with the expected random contribution, even if a few events for some of the station pairs exhibit a small p-value. This is reasonable, since any real (small) effect would be masked when merged with a larger statistical sample where no effect is present, as in the present case, where no *a priori* information exists on the relative distance between sites and relative orientation between showers axes where this effect could be enhanced.

One may also speculate about the GZ nature of these events (see sect. 3.4) which, in principle, could be enhanced along the solar or antisolar directions. Calculations reported by LAAS [18] show that the GZ probabilities may be strongly enhanced (even by orders of magnitude), especially along the solar direction and (to a lesser extent) along the anti-solar direction, because of head-on collisions of nuclei with solar photons.

Taking into account the difference between the Italian local time and the UTC time, we plotted as red squares in fig. 7 the distribution of the observed most significant EEE events along the daytime. It may be observed that the time of observation of these events along the day is distributed over the 24 hours with a small predominance during night time. For the sake of comparison, we also reported as blue triangles in the same plot the six events reported by the LAAS Collaboration [16] after correcting for the Japan local time with respect to UTC. Even though the statistics is too low to draw any significant conclusion about the time distribution along the day, it is interesting to note that also in this case a small enhancement during night time is observed.

5 Conclusion and future prospects

A first analysis of a representative dataset of cosmic ray events detected by EEE telescope clusters located at large relative distances, from 86 to 1200 km, has been carried out. Taking into account the overall common live time between all telescope pairs, this amounts to more than a decade of observations, spanning a wide interval of distances. Time and orientation correlations between distant sites were investigated under different analysis strategies. A few candidate events which are characterized by small values of the time difference —and in several cases also by a small angular difference— were extracted from the analysis. Although the statistics is too low, the observation of this kind of events to search for anomalies is one of the purposes of our experiment. A clear evidence for long distance correlations needs higher statistics.

The number of observed candidate events in this dataset was indeed very small, so that the quantitative study of such process is really at the limit of the observational possibilities, even with a large geographical coverage. An increase in the available statistics in the EEE project could come within the next years from longer data taking periods, larger duty cycles and greater telescope detection efficiency, as well as from the inclusion of additional clusters in the distribution of the EEE sites. Concerning the possible gain in all these factors, it should be observed that the present analysis was made with data collected in a period of about two years and many telescopes operating with a duty cycle sensibly smaller than 100%. A significant increase in the collected statistics would require several years. Additional EEE sites are now entering into their operational phase, with some of them including two or more telescopes in the same area. This would double the number of cluster sites, with an increase by a factor 4 in the number of possible combinations. An overall increase in the statistics collected in the next few years could then lead to an order of magnitude gain.

Further work on this subject will proceed, taking into account the additional available statistics, also with a combined analysis of the observed events from all site pairs, in order to check their overall statistical significance.

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