Eur. Phys. J. Plus (2026) 141:790
https://doi.org/10.1140/epjp/s13360-026-07922-z

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Observation of the May 2024 Forbush event with the EEE detectors operated with an eco-friendly gas mixture

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Received: 24 May 2026 / Accepted: 29 May 2026

Abstract The Extreme Energy Events Project (EEE) is devoted to studying cosmic-ray fluxes using a large network of measuring stations equipped with Multigap Resistive Plate Chambers (MRPCs) and positioned across Italy, mainly inside high-school institutes. This paper presents the first measurements obtained operating the MRPCs with an eco-friendly gas mixture, namely the observation of the charged cosmic-ray rate variation (Forbush decrease) associated with the intense geomagnetic storm that occurred in May

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Published online: 09 July 2026

2024. It is the first time a large-scale experiment has been successfully operated with a new eco-friendly gas mixture, keeping its physics performance substantially unchanged.

1 Introduction

The Extreme Energy Events (EEE) Project combines in a unique way an experiment for the measurements of cosmic-ray rates over a large area, with a dedicated outreach programme [1]. Strongly supported by two Italian research institutes within the Ministry of University and Research namely the Enrico Fermi Historical Museum of Physics, and Research and Study Centre - CREF and the National Institute for Nuclear Physics - INFN, in 2024 the Project celebrated its 20^{th} anniversary of operation [2]. EEE is based on a set of more than 50 measuring stations (telescopes) distributed in Italy and mainly installed in high-school institutes. Each telescope consists of three Multigap Resistive Plate Chambers (MRPCs) with a local readout system capable to send in an automatic way the data collected to a computer centre, located at INFN-CNAF in Bologna, for track reconstruction. Thanks to a GPS system, data from all telescopes can be analysed in a coherent way, also allowing the study of correlated events. More details on the hardware construction and performance are available in [3].

The EEE Project is also an outreach project, since high-school students and teachers have been involved from the very beginning in the construction of the MRPCs (at CERN, Geneva), in the installation and commissioning of the telescopes inside their institute and in the monitoring of the telescope operation. Data acquisition is organized in coordinated run periods that last one year and the students are invited to monthly online (or in presence) meetings to discuss and report on the telescopes status and progresses. The meetings are also enriched with specific seminars (by researchers or by students themselves) or contests to keep the interest of the students all over the year [2].

Until 2019 the telescopes were operating with a gas mixture made of 98% $C_2H_2F_4$ and 2% SF_6. However, due to its high Global Warming Potential (GWP) which led to $C_2H_2F_4$ being phased out because of regulations by the European Community, the EEE Collaboration started an extensive R&D on alternative mixtures environmentally sustainable and compatible with the current experimental setup and operation. Similar R&D was performed by other collaborations interested in developing eco-friendly gas mixtures for high energy physics experiment (see [4] and references therein). The gas chosen to replace $C_2H_2F_4$ was $C_3H_2F_4$, in its isomeric form also commercially known as HFO1234ze. Since mixtures made out primarily of HFO would result in too high operating voltages incompatible with the present power supply system of the EEE experiment, it was decided to mix it with He with a 50% fraction, following the idea outlined in [5]. The validity of this approach was also demonstrated in [6].

The detailed report of the tests performed in the EEE experiment on this topic with this mixture is available in [7].

After these tests, the new mixture was progressively introduced into the EEE telescopes' MRPCs and for the past couple of years, extensive tests have been underway and are still ongoing to certify the validity of the mixture on a large sample of chambers and telescopes.

Starting on May 8, 2024, during solar cycle 25, a series of intense events with X-class solar flares, coronal mass ejections and geomagnetic storm components occurred [8, 9]. Such events may induce a significant decrease in the cosmic-ray flux. They are named *Forbush events* since their discovery in 1937–1938 [10, 11]. The occurrence of a strong Forbush event in May 2024 was a unique opportunity to test the uniformity of the telescopes' response with the new gas mixture. The event should have been seen contemporarily by all the telescopes in operation, with comparable amplitudes, because of the similar detection conditions of the various telescopes and similar latitude, longitude and altitude ranges of the various installations. This paper reports the results of such a first analysis performed with 10 telescopes operating all along the Italian peninsula.

Notice that a detailed observation of the same Forbush event was reported by the EEE Collaboration using the POLA-R scintillator-based detectors installed since 2019 at the Svalbard Islands [12], a measurement performed at a very high latitude for the first time. In reference [12] also a comparison with neutron counters is reported.

The EEE Collaboration already observed Forbush events in the past with the original gas mixture [13]. It was thus important to verify that the performance of the chambers is maintained with the new gas mixture, allowing the observation of similar events. The occurrence of the intense Forbush decrease on May 2024 was the occasion to compare the measurements obtained by several telescopes.

2 Experimental setup and data analysis

The EEE telescopes are composed of three MRPCs with an effective area of (0.82×1.58) m^2 and with six 300 μm or 250 μm gas gaps. Each MRPC is equipped with 24 copper strips of (160×2.5) cm^2 to collect the electric signals generated by the passage of particles through the detector. A single track is defined by the presence of hits in each of the three MRPC chambers of the telescope. The particle impact point is reconstructed by the position of the hit strip and by the difference in the arrival times of the signals at both ends of the strip. A more detailed description of the EEE telescopes, the trigger, the track reconstruction and the associated data analysis is reported in [3].

Table 1 Geographical coordinates of the telescopes used for the Forbush event observation

EEE station	Latitude	Longitude	Altitude (m)
BOLO-01	44.50° N	11.35° E	112
BOLO-02	44.48° N	11.37° E	78
BOLO-03	44.49° N	11.35° E	119
CAGL-01	39.23° N	9.11° E	56
COSE-01	39.31° N	16.25° E	228
LAQU-01	42.36° N	13.41° E	722
REND-01	39.36° N	16.12° E	301
SALE-03	40.77° N	14.79° E	271
TREV-01	45.67° N	12.24° E	17
VICE-01	45.56° N	11.53° E	47

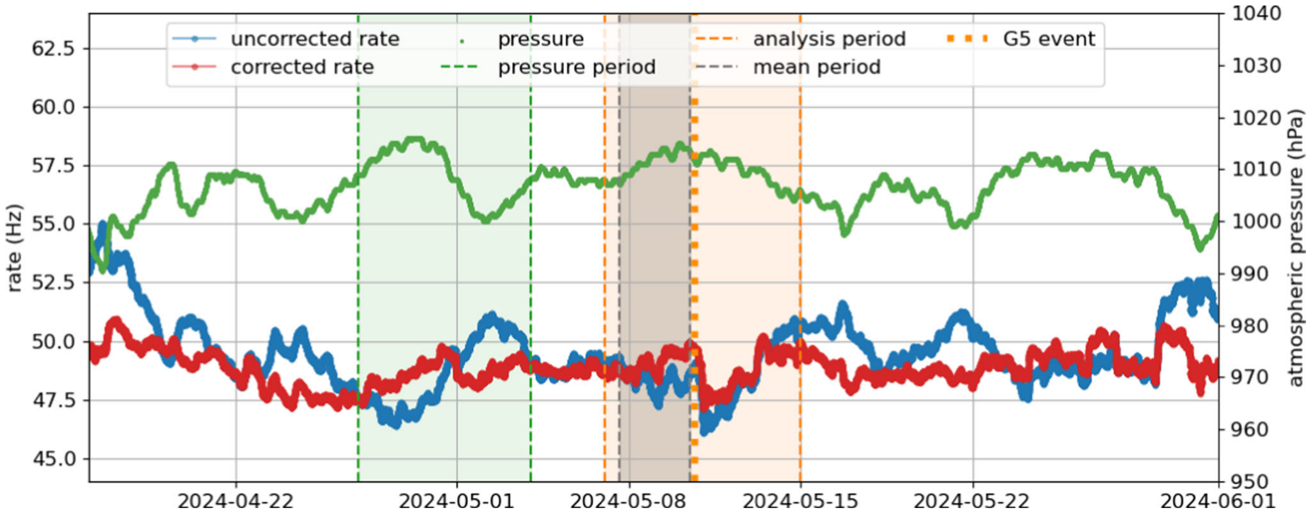

Fig. 1 Rates and pressure values recorded by one of the EEE telescopes in the network (VICE-01) as a function of the date. Blue and red data show the muon rates, before and after the barometric correction, respectively, whereas the green curve reports the atmospheric pressure. The periods corresponding to the barometric correction evaluation and to the G5 Forbush event are marked in green and orange, respectively. For the grey band (within the orange one), see Sect. 3 in the text

The telescopes involved for the analysis of Forbush event are listed in Table 1: they were chosen among those performing stable measurements during the Forbush event and are distributed all across Italy.

In the present analysis, the cosmic-muon rate is studied as a function of time. All time series are sampled to a resolution of 30 min.

Specific time windows were selected to take into account the impact of pressure variations on each telescope. For some telescopes, data gaps required that these windows be determined individually on a case-by-case basis.

In Fig. 1, the reconstructed muon rate trend of one of the EEE telescopes (VICE-01) is shown; both uncorrected (in blue) and pressure-corrected muon rates (in red) are reported, together with atmospheric pressure (depicted by the green curve). The green time window highlights the period during which the barometric correction was evaluated. It was selected outside the Forbush event, during a period of relevant atmospheric pressure variation, thus providing an excellent basis for computing the anti-correlation coefficient. The pressure correction method is described in the next section. The orange time window marks the period selected as the focus of the analysis, between May 7, 2024, and May 14, 2024, centred around the Forbush event. The peak of the extreme intensity (G5) geomagnetic storm was estimated to occur on May 10, 2024, at 17:05 UTC [8] and is indicated by the orange dotted line: a distinct and abrupt decrease in the rate is observed immediately following this point. The grey time window, preceding the Forbush decrease, was chosen as a reference to calculate the mean muon rate, which serves as the basis for the differential rate used in the comparison of different telescopes.

3 Barometric correction and computational method

In the following, the methods used to define the barometric correction for each telescope and the analysis approach to compare the different measurements are described.

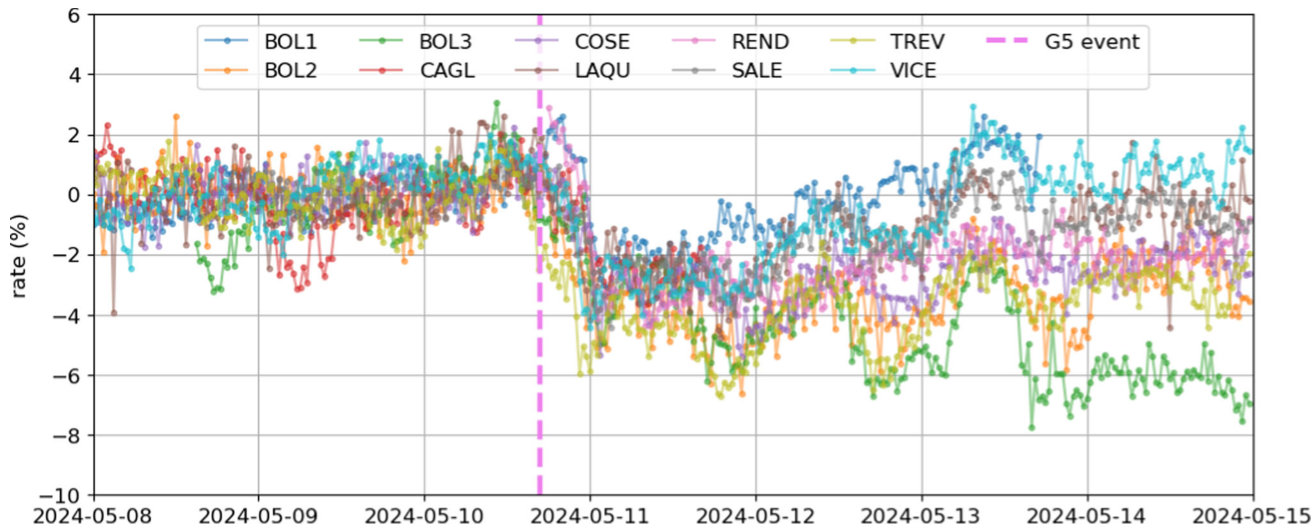

Fig. 2 Differential pressure-corrected rates for all EEE telescopes

The pressure influence on the muon intensity observed at ground level is defined as:

$$I_P = I_0\, e^{-0.01\ \beta\ (P-P_0)} \tag{1}$$

where I_P is the muon count rate expected when the atmospheric pressure (hPa) is equal to P, considering an initial count rate I_0 observed when the atmospheric pressure is equal to a chosen value P_0. β is the barometric coefficient (%/hPa) that takes into account the magnitude of pressure influence.

The barometric correction coefficient β is evaluated in the green region of Fig. 1 as the slope coefficient of the simple linear regression between $\log(\Delta I/\langle I\rangle)$ and $\Delta P = P - \langle P\rangle$, where $\langle I\rangle$ and $\langle P\rangle$ are the mean rate and the mean pressure in the selected time interval [14].

When β is found, the correction can be applied to the original time series. The pressure-corrected rate $I_{\mathrm{PC}}(t)$ is given by equation

$$I_{\mathrm{PC}}(t) = I_{\mathrm{OBS}}(t)\, e^{0.01\ \beta\ (P(t)-\langle P\rangle)} \tag{2}$$

and is also reported in Fig. 1.

In order to compare directly the rate trends of different telescopes, for each telescope the differential rate was computed as follows:

$$\Delta I(t) = \frac{I_{\mathrm{PC}}(t) - \langle I_{\mathrm{PC}}\rangle}{\langle I_{\mathrm{PC}}\rangle} \times 100 \tag{3}$$

where I_{PC} is the pressure-corrected rate, and its mean value is estimated in the period just preceding the Forbush decrease (the grey band of Fig. 1). We expect the differential rates to be characterized by zero mean almost everywhere, except during the Forbush decrease.

4 Results

The Forbush event resulting from the G5 storm of May 2024 was clearly observed by all the EEE stations as shown in Fig. 2, where the differential pressure-corrected rates for all telescopes involved in this study are plotted. The measurements from the various EEE telescopes are in good agreement with one another, although small fluctuations are present, also due to local residuals in the correction procedure. The figure demonstrates a high degree of uniformity in response and performance, achieved with a new eco-friendly gas mixture used for the first time on a large area experiment with several measuring stations.

Figure 3 reports the average corrected differential rate, which is computed by combining the data from all the EEE telescopes involved in this study, providing a general overview of the overall behaviour of the EEE experimental network. The average rate (red dots) is computed from the sum of the pressure-corrected differential rates within the same time interval of 30 min, divided by the number of telescopes, $N = 10$; the standard deviation (blue bars) is defined as $\sigma = \sqrt{\sum(I - \langle I\rangle)^2/N}$, where I is the differential rate of each telescope, and the statistical error on the mean (orange bars) is equivalent to $\sigma/\sqrt{N}$. Notice that using our entire EEE network of 10 telescopes allows to reach sensitivity at the % level, as shown in Fig. 3 in the pre-Forbush period. In the same Figure, in addition to the evident sharp Forbush decrease recorded in all the telescopes on May 10, one can also see that the effect of the Forbush is still present even 3–4 days after the main peak, with the rate not fully recovering to its pre-Forbush value.

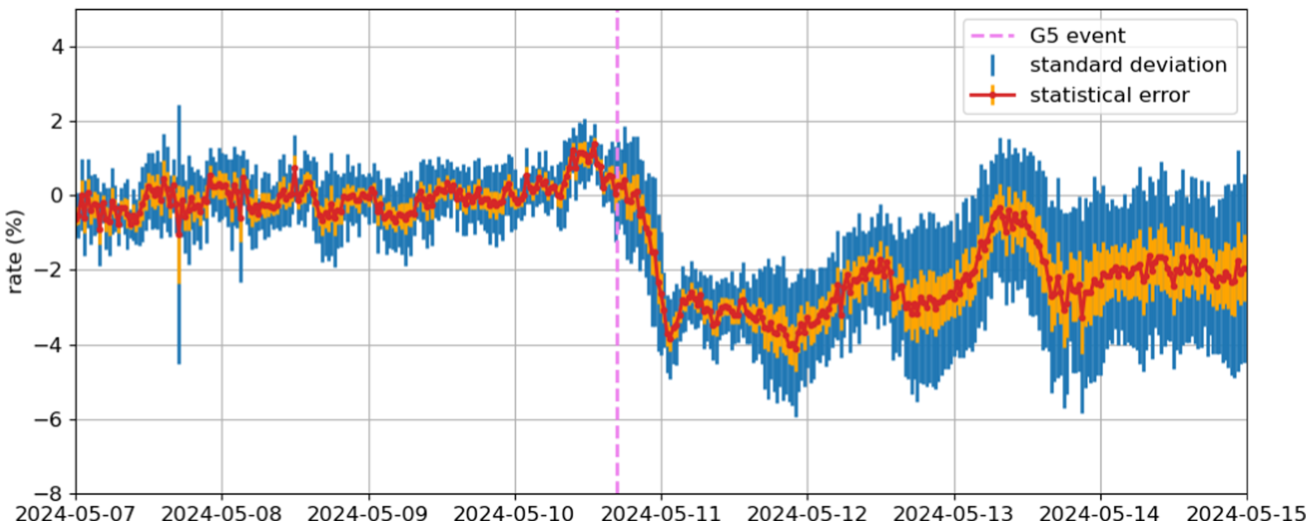

Fig. 3 Average corrected differential rate, computed with all EEE telescopes. The meaning of the legends is explained in the text

During the G5 storm of May 2024, a Forbush decrease was also detected by the EEE POLA-R scintillation detectors, installed in the Svalbard archipelago, close to the North Pole. The data collected by those detectors show a strong correlation with measurements by neutron detectors located in the same site [12] and with the data reported in the present paper. A specific correlation analysis among the various measurements (Svalbard muons, Svalbard neutrons, Italy muons) is in progress.

5 Conclusion

The analysis presented in this paper took advantage of the exceptional Forbush event occurred in May 2024 to assess and compare the performance of various telescopes of the EEE Project. For its Multigap Resistive Plate Chambers, joining the efforts of the gaseous detector community, the EEE Collaboration successfully identified a new eco-friendly gas mixture based on HFO and He. This is the first large-scale application to cosmic-ray physics obtained with this new gas mixture. The results reported here demonstrate the capability of all telescopes to measure the small variations of rate associated to such a Forbush event and a good uniformity of response among the various telescopes. A more quantitative analysis of the results concerning the observation of the May 2024 Forbush event is in progress and will be reported in a forthcoming paper.

Acknowledgements The authors would like to thank the students and teachers of the ten high schools whose telescopes were in full operation, thus making possible this analysis.

Funding Open access funding provided by Università degli Studi di Salerno within the CRUI-CARE Agreement.

Data availability This manuscript has associated data in a data repository. [Authors' comment: Data are freely available at the EEE monitor website: https://eee.centrofermi.it/monitor/].

References

1. Zichichi, A.: Extreme Energy Events - La Scienza nelle Scuole (2017). https://eee.centrofermi.it/images/EEE-PaperAZ/EEE_Paper_AZ-2017.pdf
2. Abbrescia, M., et al.: Bringing the science to the hearts of young people The Extreme Energy Events project (2004-2024). Submitted to Supplemento al Giornale de Fisica (2024)
3. M. Abbrescia, Performance of the multigap resistive plate chambers of the extreme energy event experiment. JINST 14(C05022), (2019). https://doi.org/10.1088/1748-0221/14/05/C05022
4. M. Abbrescia, High-rate tests on resistive plate chambers operated with eco-friendly gas mixtures. Eur. Phys. J. C **84**, 300 (2024). https://doi.org/10.1140/epjc/s10052-024-12545-8
5. M. Abbrescia, New gas mixtures for resistive plate chambers operated in avalanche mode. Nucl. Inst. Methods Phys. Res. A **661**, 190–193 (2012). https://doi.org/10.1016/j.nima.2010.08.074

6. M. Abbrescia, Eco-friendly gas mixtures for resistive plate chambers based on tetrafluoropropene and Helium. JINST 11(P08019), (2016). https://doi.org/10.1088/1748-0221/11/08/P08019
7. Abbrescia, M., et al.: First results on new helium based eco-gas mixtures for the extreme energy events project. JINST **19**(P11003) (2024) https://doi.org/10.1088/1748-0221/19/11/P11003
8. H. Hayakawa, The solar and geomagnetic storms in May 2024: A Flash Data Report (2024), arXiv:2407.07665
9. J.S. Kwak, Observational overview of the May 2024 G5-level geomagnetic storm: from solar eruptions to terrestrial consequences. J. Astron. Sp. Sci. **41**, 171 (2024)
10. S.E. Forbush, On the effects in cosmic-ray intensity observed during the recent magnetic storm. Phys. Rev. **51**, 1108 (1937)
11. S.E. Forbush, On world-wide changes in cosmic-ray intensity. Phys. Rev. **54**, 975 (1938)
12. F. Riggi, High latitude observation of the Forbush decrease during the May 2024 solar storms with muon and neutron detectors on Svalbard. Adv. Sp. Res. (2025). https://doi.org/10.1016/j.asr.2025.05.023
13. Abbrescia, M., et al.: Observation of the february 2011 forbush decrease by the eee telescopes. Eur. Phys. J. Plus **126**(61) (2011) https://doi.org/10-1140/epjp/i2011-11061-5
14. deMendonça, R.R.S., et al.: Temperature effect in secondary cosmic rays (muons) observed at the ground: analysis of the global muon detector network data. The Astrophys. J. **830**(2) (2016) https://doi.org/10.3847/0004-637X/830/2/88