PROCEEDINGS OF SCIENCE

Recent results from the PolarquEEEst measurement campaign at large geographical latitudes

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PoS(ICRC2023)232

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The Extreme Energy Events (EEE) Project, mainly based on a network of cosmic ray telescopes, consisting of MRPC gaseous detectors built by high school students at CERN and taking data for more than 15 years, has recently employed additional scintillation detectors for several measurement campaigns and long-term investigations of secondary cosmic rays over a large range of northern latitudes. Muon rate measurements at the sea level were first performed by the PolarquEEEst expedition on a sailboat from 66° to 82° N, and extended in a subsequent expedition by car, covering an overall latitude range from 35° to 82°N. Since 2019, three additional detectors, similar to those used in these expeditions, were permanently installed at Ny-Ålesund (79°N, Svalbard islands). Besides the prolonged monitoring of cosmic ray activity at such northern latitudes, these devices were also able to record the Rayleigh-Lamb waves generated by the 2022 Hunga-Tonga volcanic eruption. Results from the last three years of data taking will be presented and discussed.

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1. The EEE Project

The Extreme Energy Events Project (EEE) [1] was born in 2004 with the idea to involve high school students into a real experiment. The main goal of the experiment is the search for cosmic ray events with very high energy using a network of telescopes made of gaseous particle detectors, namely Multigap Resistive Plate Chambers (MRPC), [2] spread over the whole Italian territory (e.g. searching for long distance correlations). The project started in 2004 with muon telescopes installed in few pilot schools and it grew in time reaching a notable size, with more than 50 telescopes installed (Fig. 1-left). Since 2014 the data acquisition is coordinated, and all data are collected and processed in quasi real time in a single endpoint at the INFN CNAF computing center in Bologna [3]. Since 2021 EEE started the transition to operate with an eco-fiendly Freon [4] to strongly suppress the impact of CO_2 equivalent emission in the atmosphere.

In 2018 a new idea started inside EEE to bring cosmic ray telescopes at extreme latitude. This was realized by the construction of a different type of telescopes, the so-called POLAR detectors, based on scintillators coupled to SiPM: the PolarquEEEst2018 expedition. The need for changing technology with respect an EEE gas detector was driven by the requirement to have it on board of a boat, the Nanuq, sailing up to 82° N. Since 2019, three of four POLAR detectors are operating at the site of Ny-Ålesund at the Svalbard archipelago.

In the next sections we will focus on the results coming in the last 4 years from PolarquEEEst data collection.

2. The PolarquEEEst data collection

At the end of July 2018, one POLAR detector, labelled as POLA-01, started its travel around the Svalbard islands while two other detectors were installed at fixed positions (in high schools) in Norway and Italy as a reference, POLA-02 and POLA-03. During its trip POLA-01 measured the cosmic muon flux at different latitudes spanning an interval of 66° − 82° N. No significant variations in the muon flux were observed [5] and in 2019 the measurement was extended at lower latitude with an expedition on the road across Europe. Figure 1-right shows the travel of POLA-01 (yellow lines). In 2019 a fourth detector was built and in June of the same year three detectors were permanently installed at Ny-Ålesund to collect data.

All detectors are connected to the EEE netwoork and their data processed in the CNAF computing center. They can be controlled remotely, limiting the maintainance *in situ* to one week per year and guaranteeing a high duty cycle (> 99% with at least one active detector).

3. Recent results with the PolarquEEEst detectors

3.1 Muon rate measurements at the sea level up to extreme latitude

By combining the measurements of the POLA-01 detector on Nanuq/Svalbard and in the European trip we were able to cover the latitude range 35° − 82° N. The results were recently published in [6] and show an increase of the rate up to 52° as shown in Fig. 2-top. The picture is consistent with an increasing geomagnetic cutoff at lower latitude. The effect is qualitatively reproduced by the PARMA model [7] used to describe the data. Such a model allows to apply

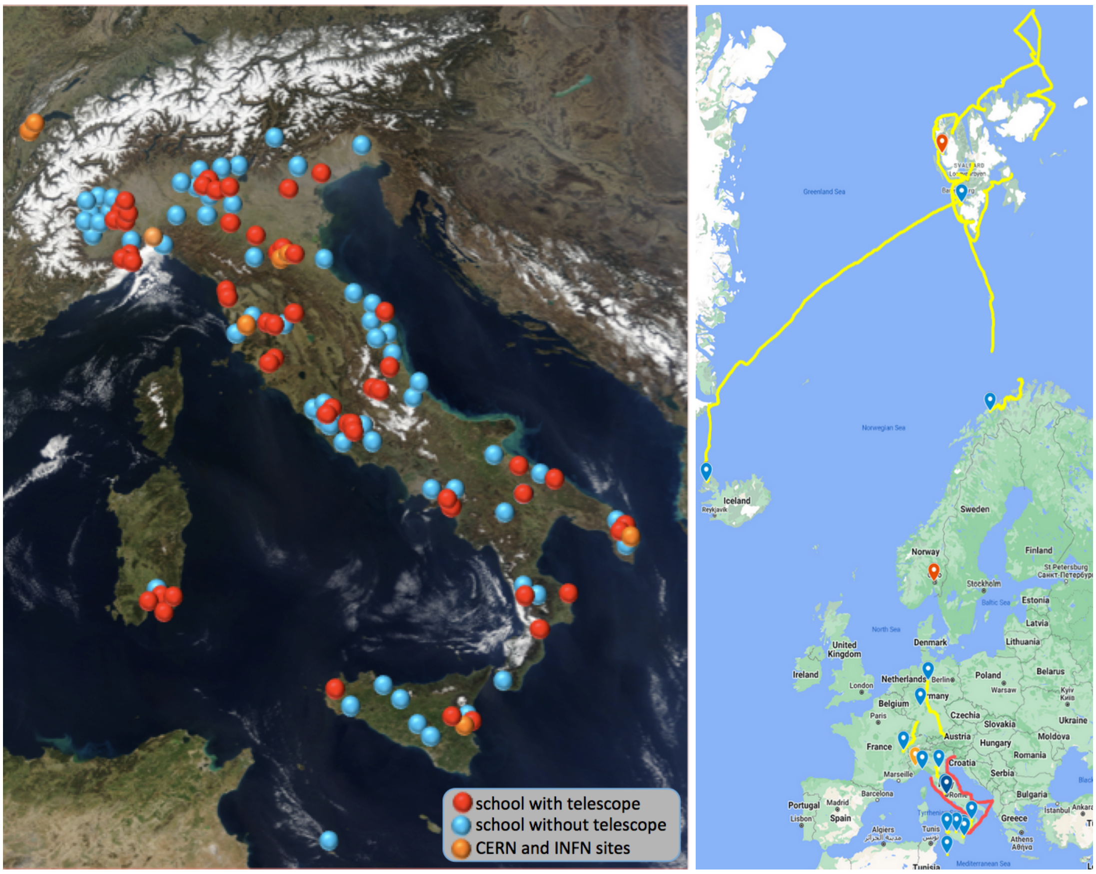

Figure 1: The EEE network is shown (left): in red (orange) high schools (laboratories) with a cosmic ray telescope installed, in cyan high schools joining the project. The PolarquEEEst coverage is reported as well (right) in the period 2018-2022: in yellow the trip of one of the 4 detectors (POLA-01) in 2018-2019, in red the trip of POLA-02 in 2022.

a geomagnetic cutoff on top of some input primary cosmic ray spectra assuming then a shower development to extract secondary components at ground. As mentioned the comparison works only at a qualitative level, and it is worth to note that the input spectra used in the model are not yet updated with the most recent measurements. It is also possible to report the measurements as a function of the cutoff rigidity corresponding to geographical coordinates, Fig. 2-bottom. The trend is consistent with the functional form suggested in [8]:

$$r(R) = r_0(1 - e^{-\alpha R^{-k}}) \tag{1}$$

where r is the rate as a function of the cutoff rigidity R and r_0, α and k are fit parameters found to be (35.15 ± 0.05) Hz, (6.8 ± 1.1) and (0.45 ± 0.08), respectively.

In order to cover the missing range 52° − 66° N a next measurement campaign is foreseen in 2024 in the Northern Europe. Since the detector used to cover the missing range will be a different one, POLA-02, a campaign of measurements was performed in 2022 on board of the Amerigo Vespucci vessel of the Italian Military Navy around Italy (red path in Fig. 1-right). The data analysis of these new data is still ongoing and it will be very useful to verify detector calibrations before of the next step.

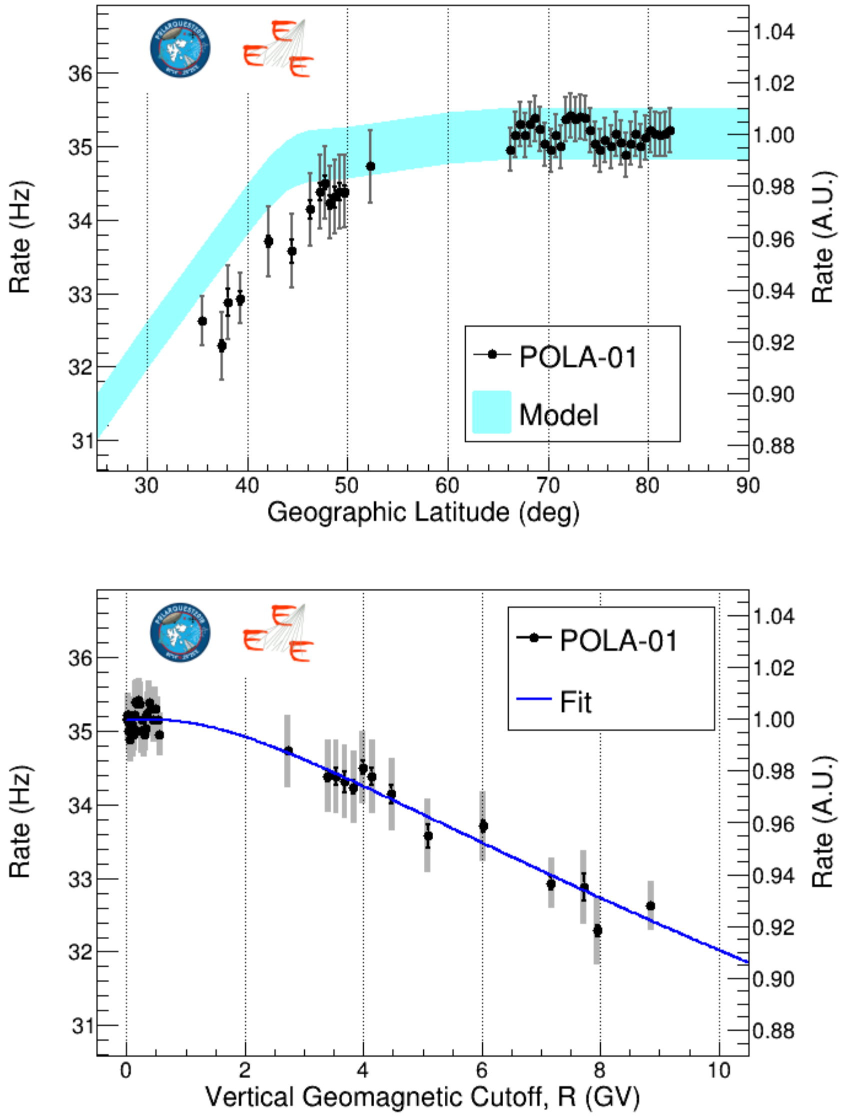

Figure 2: Cosmic particle rate measured by the POLA-01 detector as a function of the geographic latitude (top panel), and as a function of the vertical geomagnetic cutoff (bottom panel) [6].

3.2 2019-2023 data at Ny-Ålesund (Svalbard)

As mentioned in the previous sections, three POLAR detectors are taking data since 2019 at Ny-Ålesund (Svalbard). In Fig. 3 the trending of the rate measured in the last 4 years is shown. Such a trending was build by averaging among the rates measured by all three detectors when available. A clear seasonal modulation (winter-summer) effect can be observed as found also in previous experiments [9]. This effect is usually ascribed, for low energy muons O(1 GeV), to a change in the temperature of the atmosphere and then in the air density: an increase of the temperature favours the production of muons at higher altitude, which then can decay with a higher probability before reaching the ground level.

The study of such an effect along time is useful to better understand this mechanism and in order to study other possible periodicity patterns in the data. The study of correlations of the muon flux with other atmospheric parameters is interesting as well. Some of these parameters are already measured by the CNR Climate Change Tower, sited close to one of our detector at Ny-Ålesund, and this kind of correlations will be deeply studied in the close future.

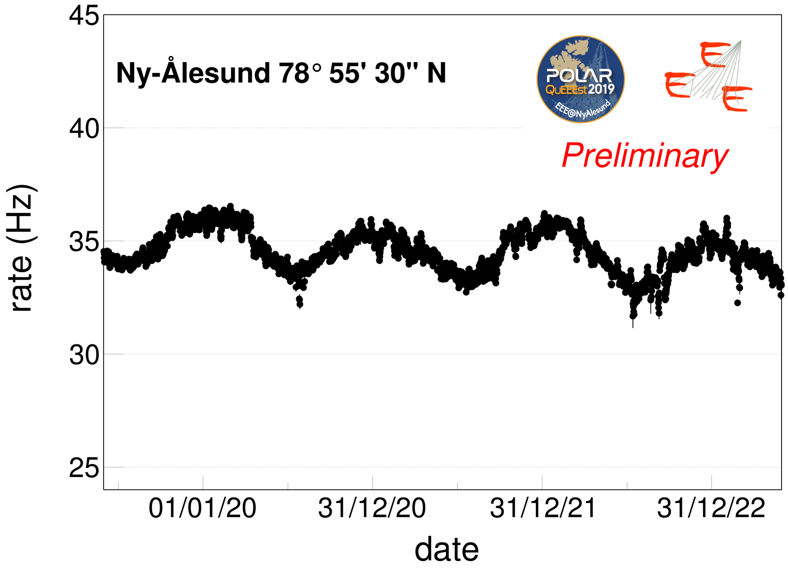

Figure 3: Muon flux as measured by the PolarquEEEst detectors at Ny-Ålesund in the period 2019-2023.

The high duty cycle of POLAR detectors is one of the key feature of our observatory in Ny-Ålesund. This capability allows us to be very reactive in case of an unexpected event trigger coming from other observatories. So far, no interesting event related to cosmic rays was triggered and observed in our station. However, on the 15th January of 2022 the Hunga-Tonga volcano (South Pacific Ocean) erupted, producing a shock-wave travelling along the globe. Such an intense event was also registered in our station and the pressure sensors of our detectors were able to catch the signal (pressure variation) with a significance larger than 3 standard deviations and an amplitude up to 1 hPa [10]. In Fig. 4 the pressure profile in the period of interest is reported. Different spikes are clearly visible in all the three detectors at the same time in correspondence of the shock-wave impulse passing through the station. This is a nice example of interdisciplinary application of our project.

4. Summary and outlooks

PolarquEEEst, as part of the EEE network, represents a unique opportunity to measure the secondary muon flux at ground up to extreme latitudes (North Hemisphere), investigating the effect of geomagnetic cutoff. The permanent installation at Ny-Ålesund of three detectors allows to study different kinds of correlations between the muon rate at ground and atmospheric/astrophysical effects. The annual modulation of the muon rate at ground was clearly observed in the last 4 years, as also shown in the past and the search for other kinds of periodicities is now started. Measuring

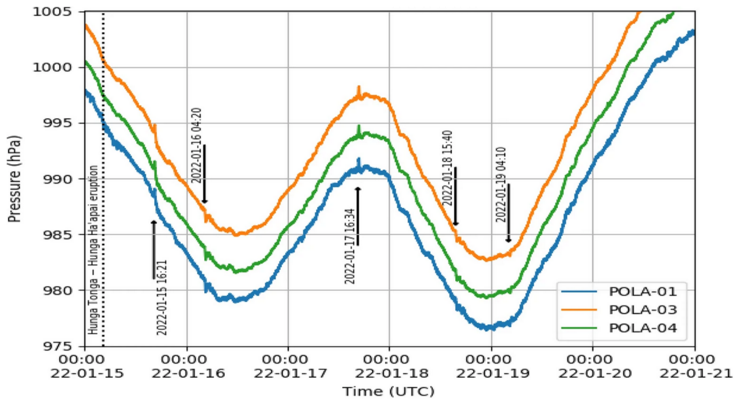

Figure 4: Real time pressure as a function of time (UTC) from January 15 to January 21, 2022 observed with POLA-01 (blue line), POLA-03 (orange line) and POLA-04 (green line), respectively [10].

the cosmic ray flux along time could also be in the future a potential monitoring tool for spotting changes related to the environment, solar activity, and more.

References

[1] A. Zichichi. ProgettoEEE – Extreme Energy Events – La Scienza nelle Scuole. Società Italiana di Fisica (2017) https://eee.centrofermi.it/images/EEE-PaperAZ/EEE_Paper_AZ-2017.pdf.

[2] M. Abbrescia *et al.*, NIM A 845 (2017) 383.

[3] F. Noferini *et al.*, NIM A824 (2016) 329.

[4] E. Bossini *et al.*, NIM A1046 (2023) 167754.

[5] M. Abbrescia *et al.*, EPJ C80 (2020) 665 [Erratum: EPJ C80 (2020) 897].

[6] M. Abbrescia *et al.*, EPJ C83 (2023) 293.

[7] T. Sato, PLOS ONE 10(12) (2015) e0144679; PLOS ONE, 11(8) (2016) e0160390.

[8] L.I. Dorman, S.G. Fedchenko, L.V. Granitsky, and G.A. Rishe., Proceedings 11th International Cosmic Ray Conference 1970.

[9] R.R.S. Mendonça *et al.*, ApJ 830 (2016) 88.

[10] M. Abbrescia *et al.*, Scientific Reports 12 (2022) 19978.