Measurement of the muon flux in the tunnels of "Doss Trento" hill.

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In the context of astroparticle physics experiments and quantum computing projects, it is important to identify possible underground laboratories where the cosmogenic induced background is suppressed. Located about 500 m far from the center of Trento (Italy) the "Piedicastello tunnels" are covered by 100 m limestone rock of the "Doss Trento" hill. The site exceeds 6000 m^2 surface and is divided across two tunnels hosting events, temporary exhibitions and educational activities. The cosmogenic background characterization was performed with three portable scintillator telescopes having different geometrical acceptances. The muon flux measured in the deepest part of the Piedicastello tunnels is about two orders of magnitude lower than the flux observed on the surface; this suggests a possible use of this site as a facility in which a low environmental background is required.

I. INTRODUCTION

In 1936 C. D. Anderson discovered the muon that is the main component of charged cosmic rays at ground. The physical properties of the muon are identical those of the electron, but the muon is 207 times as massive as the electron, for this reason the Nobel laureate I. I. Rabi famously quipped: "who ordered that?" when informed of the discovery. There is another famous saying that perfectly applies to the 70 m^{-2}s^{-1}sr^{-1} muon flux at sea level: "Yesterday's sensation is today's calibration" (R. P. Feynman) "... and tomorrow's background" (V. L. Telegdi) . In particular being relativistic and almost vertical, atmospheric muons are a particle beam that is provided for free by Nature, useful for the calibration of particle detectors. However they are also a penetrating background source for many astroparticle physics experiments and a noise source for some devices. In particular, in the context of quantum computing, it is known that cosmic rays are responsible for a sizable fraction of correlated errors in Superconducting Qubit arrays [1, 2].

For these reasons it is useful to identify possible underground laboratories to shield experiments from the penetrating muon flux. In particular, for quantum computing projects and for some astroparticle physics applications (see e.g. [3, 4]) a suppression of the muon flux by a factor 10-100 is enough. Therefore a laboratory as deep as INFN-LNGS [5] is not strictly necessary and another eas-

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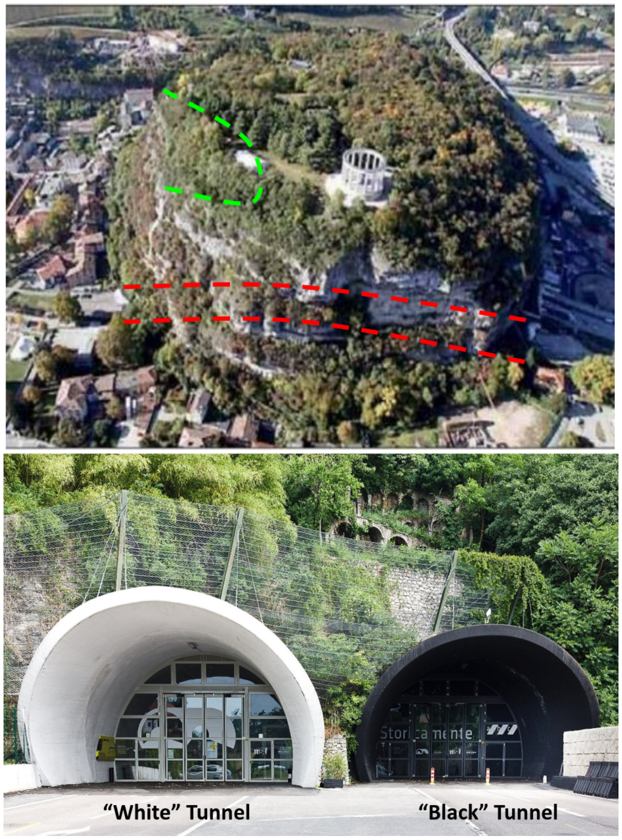

FIG. 1. The aerial view of the "Doss Trento" hill, embedded within the Piedicastello district near the Trento train station. Red dashed lines show the underground path of the two Piedicastello ("White" and "Black") tunnels, while green dashed line shows the path of the old tunnel crossed by the "Alpini road".

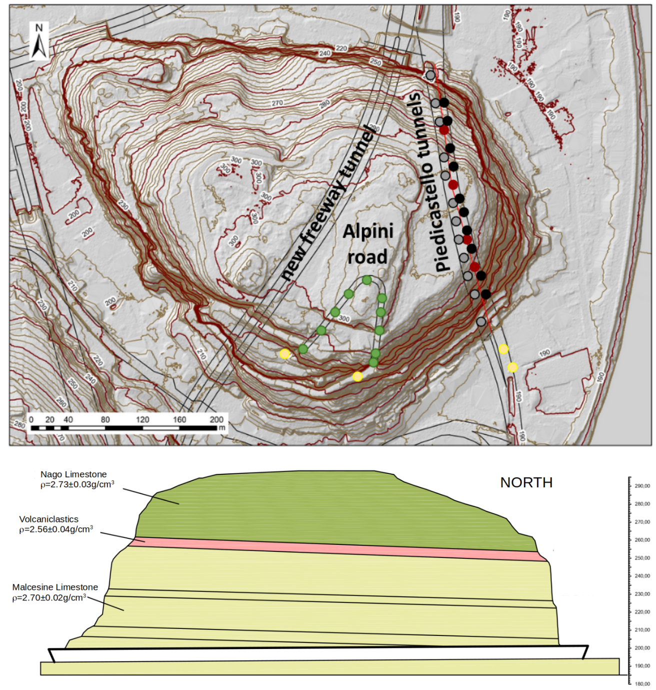

FIG. 2. Topographic map of the "Doss Trento" hill. The circles depict the sites of muon flux measurement. Yellow circles for external measurements, green circles for measurements in the old tunnel of the "Alpini road", gray circles for measurements in the "White tunnel", black circles for measurements in the "Black tunnel", brown circles for measurements in the cross passages between Black and White tunnels. Bottom figure shows the geological section of the rocks above the "Piedicastello tunnels".

ily accessible site, with renovated waterproofed walls and equipped with electrical power and services is preferable, once the reasonable shielding of 100 m of rock is achieved.

The Trento University and INFN-TIFPA are involved in different astroparticle physics and quantum computing projects (see e.g. "Quantum Science and Technology in Trento" [6]) therefore the cosmogenic background in the tunnels of the "Doss Trento" hill (see Fig.1) is investigated in this work.

II. TUNNELS IN THE "DOSS TRENTO" HILL

The "Doss Trento" ("Dòs Trent" in local dialect, original Roman name is "Monte Verruca") is a small hill that rises on the right bank of the Adige river near the city center of Trento. It is a limestone spur, that reaches 309 meters above sea level, rising to more than a hundred meters above the floor of the valley. During the Great War, the "Doss Trent"o was part of an impressive defense system and the "Alpini road" were built in 1940 crossing a 170 m long bandy tunnel. This old tunnel is located 55 m below the hill top, the water dripping walls are raw and the tunnel is still used to reach the Mausoleum of Cesare Battisti (an Italian patriot) on the top of the "Doss Trento".

In the 60s two 300 m long tunnels were dug, near the Piedicastello district, allowing the freeway crossing the "Doss Trento". These "Piedicastello tunnels" were in use until 2007 when two new freeway tunnels were excavated crossing the core of the "Doss Trento". In 2008 the "Piedicastello tunnels" were converted into two modern exhibition spaces known as the "Galleria Nera" (Black Tunnel) and the "Galleria Bianca" (White Tunnel). The walls of the "Piedicastello tunnels" are clean and dry, the 6000 m^2 exhibition spaces contain conference rooms and services and are equipped with electric current and data connection. The map of the "Doss Trento" tunnels and the geological section of the limestone rock over the "Piedicastello tunnels" are shown in Fig. 2.

The geological section of the rocks above the "Piedicastello tunnels" (bottom panel of Fig. 2) suggest an homogeneous rock density ($\rho \simeq 2.7$g/cm^3) with a composition dominated by limestone.

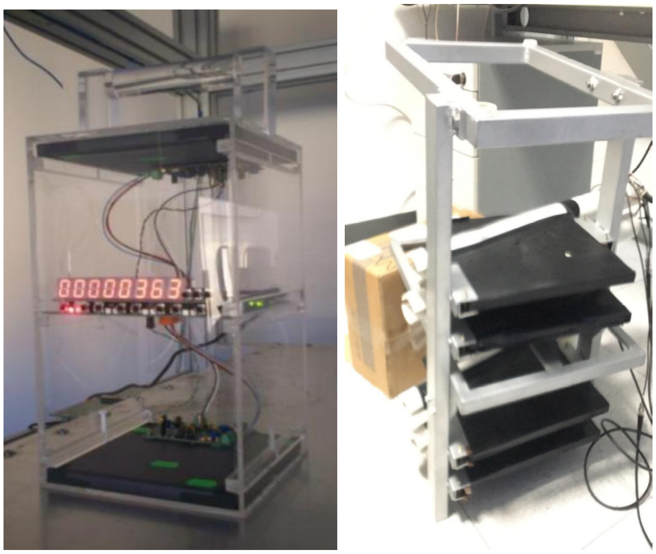

FIG. 3. Cosmic box (left) and TIFPA0 (right) detectors.

III. MUON FLUX MEASUREMENTS

The project of characterization of the tunnels in the "Doss Trento" hill was part of the "Cosmic box contest" organized by the EEE (Extreme Energy Events) collaboration [7] with the Leonardo da Vinci high school of Trento. A "Cosmic box" detector (see Fig. 3.left) made by two layers of a 15 x 15cm^2 plastic scintillator working in coincidence with telescopic configuration at a distance of 19 cm, was operated by the students under the supervision of INFN-TIFPA researchers. With the aim to collect reasonable statistics, two additional muon detectors were built at INFN-TIFPA: TIFPA0 (see Fig. 3.right) made by four layers of 25x30cm^2 plastic scintillator working in coincidence with telescopic configuration at a distance of 31 cm, and TIFPA1 made by two layers of 25x30cm^2 plastic scintillator, both in coincidence, simply superimposed to allow the maximum geometrical acceptance. The angular field of view of TIFPA0 is similar to the "Cosmic box" one while the angular field of view of TIFPA1 is almost 2π. For all the detectors the plastic scintillator used was EJ-200, by Eljen Technology, with 1cm thickness. The "Cosmic box" and TIFPA1 readouts are based on the NUV3S-P Silicon PhotoMultiplier (SiPM) by ADVANSID, with a surface of 3x3 mm^2 and pixel size equal to 40 μm, while TIFPA0 readout is based on P30CW5 Sens-Tech PhotoMultiplier tubes (25 mm diameter).

When placed outdoors, the counting rate of TIFPA0 and TIFPA1 detectors is $\simeq$ 4Hz while the counting rate of the "Cosmic box" detector is $\simeq$ 0.5Hz. The background rate of TIFPA0 and TIFPA1 is less than $6{\times}10^{-4}$Hz, this was verified in the deepest part of the "White tunnel" intentionally mis-aligning a layer of the telescopes. No counts were measured during a 30 minutes long "background-run" with this configuration.

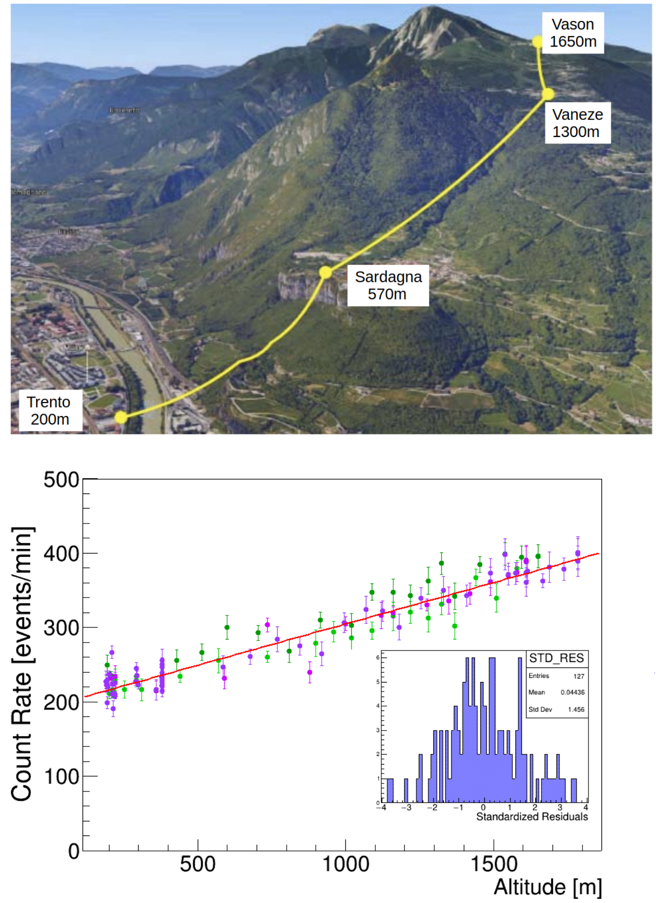

FIG. 4. Outdoor muon flux measurement at different altitudes ascending from Trento (200m) to Vason (1650m, green points) or to Forcella Valbona (1760m, magenta points). In the inset the standardized residual distribution.

A. Outdoor muon flux measurements

A preliminary outdoor muon flux measurement was acquired with TIFPA0 and TIFPA1 detectors at different altitudes ascending from Trento (200m) to Vason (1650m, green points in Fig. 4) or to Forcella Valbona (1775m, magenta points in Fig. 4). The muon counting rate doubles when the detectors are placed at $\simeq$ 2km of altitude above Trento. Beyond the educational content of this measurement (that is an evidence for the relativistic dilatation of muon lifetime) it is interesting to compare this result with the underground flux measurements, when considering that 2km of air provides less grammage than 1m of limestone rock. This measurement also allows a check of the stability of the detectors (see the inset in Fig. 4) limiting the possible systematic errors on the muon rate measurements within the same session to be below 5%.

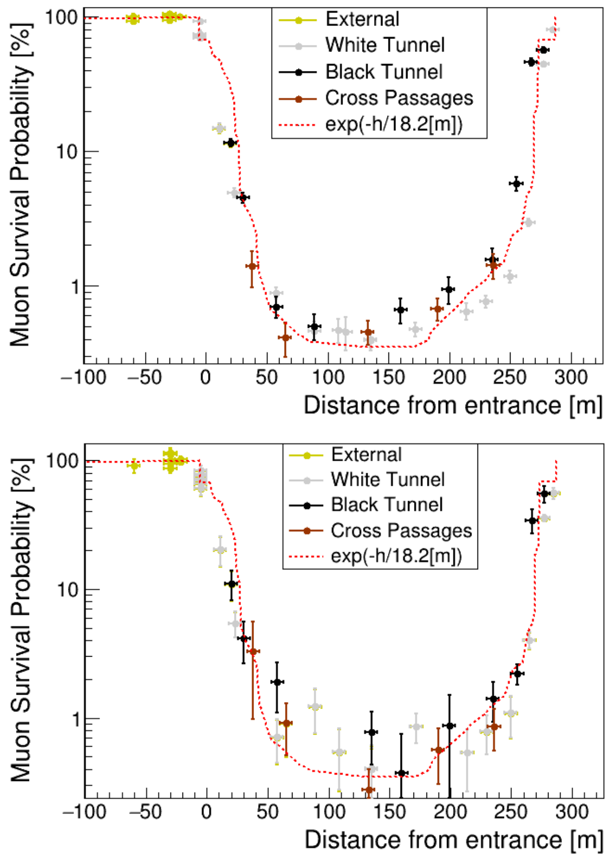

FIG. 5. Survival probability for vertical muons measured by TIFPA0 (top plot) and "Cosmic box" (bottom plot) detectors in the "Piedicastello tunnels". The dashed red line shows the muon flux expected by a simple exponential attenuation model based on the rock profile of Fig. 2.

B. Measurements in the "Piedicastello tunnels"

The underground muon flux measurements were performed in 7 different days for the 40 positions depicted in Fig. 2. In each measurement day, the external flux was recorded at the start and at the end of the session to limit the systematic error on the flux ratio evaluations. The measurements were performed with the three detectors in the "White" and "Black" tunnels of Piedicastello, while the measurements were performed only with TIFPA0 and TIFPA1 detectors in the "Alpini road" tunnel since the sporadic vehicular traffic prevents the long exposures required by the "Cosmic box" detector.

Figure 5 shows the survival probability for vertical muons measured by the TIFPA0 and "Cosmic box" detectors in the "Piedicastello tunnels". The overall behaviours are well described by a simple exponential attenuation model based on the rock profile of Fig. 2. The two measurements are in good agreement considering that the angular field of view of both detectors are similar. The statistical uncertainty obtained by "Cosmic box" detector is larger due to the smaller detector size. In the central part of both tunnels the vertical muon flux is strongly suppressed to 0.5% of the external muon flux.

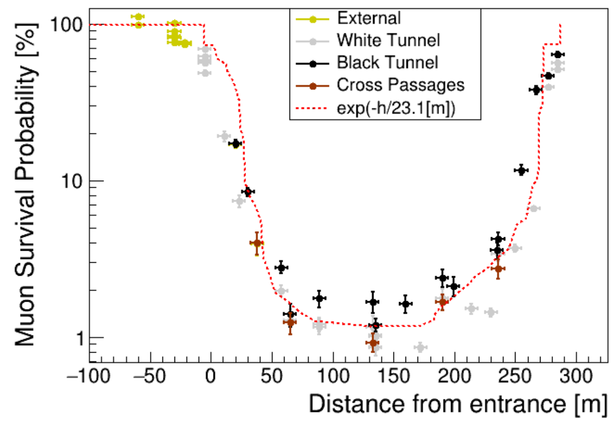

FIG. 6. Muon survival probability measured by the (large field of view) TIFPA1 detector in the Piedicastello tunnels. The dashed red line shows the muon flux expected by a simple exponential attenuation model based on the rock profile of Fig. 2.

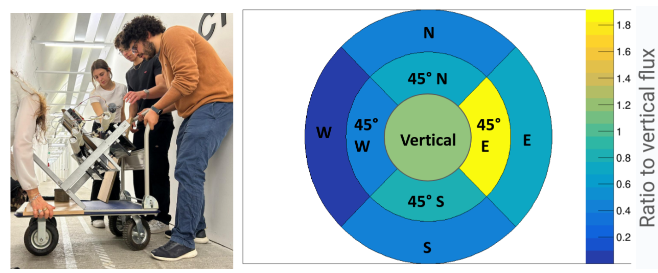

FIG. 7. Measurement of angular distribution of muon flux in the center of the "White tunnel" with the TIFPA0 detector.

In Figure 6 the muon survival probability measured by the TIFPA1 detector is shown. It is important to remember that thanks to the wide field of view, the TIFPA1 detector can be triggered by very inclined muon tracks that cross the relatively thin east cliff of the "Doss Trento" hill. For this reason the maximum suppression of the muon flux measured by the TIFPA1 detector is of the order of 1% of the external muon flux.

For a similar reason all the detector measurements also suggest that a slightly larger shielding is provided by the "White tunnel" as compared to the "Black tunnel". This is more evident for the measurements made in the north halves of the tunnels where a small thickness of the east wall of the "Doss Trento" hill is expected.

To further verify this hypothesis a set of measurements were collected in the center of the "White tunnel" by tilting the TIFPA0 detector of 45° and 90° and orienting it towards the four cardinal directions (see Fig. 7). It was found that the flux of ~45° muons from the East direction is twice the vertical muon flux and that a sizable fraction of muons is collected by horizontally placing the TIFPA0

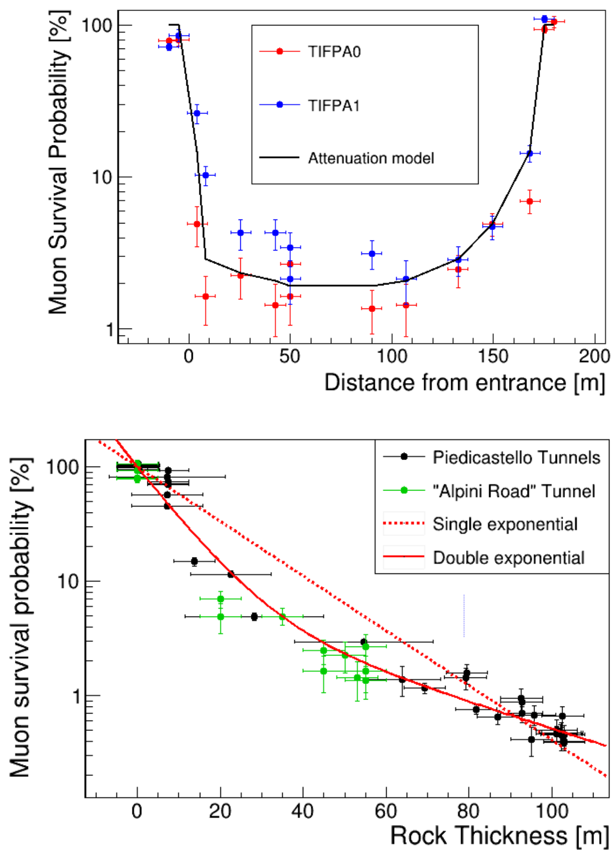

FIG. 8. Measurements of muon survival probabilities in the ”Alpini road” tunnel (top plot). Vertical muon survival probability as a function of rock thickness (bottom plot).

detector.

C. Measurements in the ”Alpini road” tunnel

The tunnel of the ”Alpini road” is quite narrow (∼4m) the walls are made of raw limestone and water is dripping from many points of the ceiling. The rock coverage is below 55m and this tunnel is subject to sporadic vehicular traffic. Therefore this tunnel is not suitable for a laboratory facility, however muon flux measurements were performed to improve the data sample for rock thicknesses in the range 10-50m.

Each measurement session in this tunnel was limited to 2-3 minutes allowing the passages of the other cars, therefore the measurements were performed only with TIFPA0 and TIFPA1 detectors.

In figure 8, top plot, the muon survival probabilities measured by TIFPA0 and TIFPA1 detectors are shown. Also for the ”Alpini road” tunnel the effect of inclined muon tracks contributing mainly to TIFPA1 triggers is visible. By combining the vertical muon survival probabilities measured by TIFPA0 detector in the ”Piedicastello tunnels” and in the ”Alpini road” tunnel, the bottom plot of figure 8 is obtained. A single exponential attenuation (red dashed line) is providing the raw and simple models plotted in Fig.5. However, a two exponential attenuation model is suggested by data: $P(h) = P_0\ exp(-h/h_0) + P_1\ exp(-h/h_1)$ where: $P_0 = (92.6\pm2.2)\%$, $P_1 = 100\% - P_0$, $h_0 = 9.1\pm1.1$ m and $h_1 = 37.6\pm4.5$ m. Attenuation profile from this model is superimposed as a continuous black line in the top plot of Fig. 5. A similar two component approximation is justified in this rock thickness range since the abundant and soft part of the muon spectrum is easily stopped within 10m of limestone rock while the harder spectrum components require a larger rock thickness to slow down in the non-relativistic regime before being stopped.

IV. CONCLUSIONS

The measurements of muon flux in the ”Piedicastello tunnels” show an attenuation of a factor ∼ 100 with respect to the external muon flux. The obtained results are similar to the ones obtained in other shallow underground laboratories. In particular at Felsenkeller site a muon flux suppressed by a factor of 40 due to the 45 m thick rock overburden is measured [4], while in the bunker of Soratte mountain a flux that is 0.5% of the external one was surviving 200m of limestone rock [3]. By considering the ease of access of the ”Piedicastello tunnels” site, which requires 15 minutes walking time from the Trento train station, and the very good internal status of the tunnels, equipped with electrical power, data connection and services, this is potentially a very promising site for a shallow underground laboratory.

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[1] P. M. Harrington, M. Li, M. Hays, W. V. D. Pontseele, D. Mayer, H. D. Pinckney, F. Contipelli, M. Gingras, B. M. Niedzielski, H. Stickler, J. L. Yoder, M. E. Schwartz,

J. A. Grover, K. Serniak, W. D. Oliver, and J. A. Formaggio, Synchronous detection of cosmic rays and correlated errors in superconducting qubit arrays (2024), arXiv:2402.03208 [quant-ph].

[2] C. D. Wilen *et al.*, Correlated charge noise and relaxation errors in superconducting qubits, Nature **594**, 369 (2021).

[3] A. Candela, A. Cocco, N. D'Ambrosio, M. De Deo, A. De Iulis, M. D'Incecco, P. Garcia Abia, C. Gustavino, G. Gustavino, M. Messina, G. Paolucci, S. Parlati, and N. Rossi, Measurement of the muon flux in the bunker of monte soratte with the crc detector, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1031**, 166514 (2022).

[4] F. Ludwig, L. Wagner, T. Al-Abdullah, G. Barnaföldi, D. Bemmerer, D. Degering, K. Schmidt, G. Surányi, T. Szücs, and K. Zuber, The muon intensity in the felsenkeller shallow underground laboratory, Astroparticle Physics **112**, 24 (2019).

[5] Formicola, A., Ianni, A., Imbriani, G., Laubenstein, M., Pirro, S., and Previtali, E., Current developments in lngs underground physics, Europhysics News **54**, 13 (2023).

[6] Quantum science and technology in trento, `https://quantumtrento.eu/`, accessed: 2024-03-30.

[7] S. Pisano and S. Pisano (on behalf of the EEE), The extreme energy events project: Bring science inside schools, Eur. Phys. J. Plus **137**, 1190 (2022), [Erratum: Eur.Phys.J.Plus 137, 1383 (2022)].