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

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ABSTRACT

In the context of astroparticle physics, nuclear astrophysics and quantum computing projects, it is important identifying underground laboratories where the cosmogenic 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 currently hosting events, temporary exhibitions, and educational activities. The cosmogenic background was measured in different locations within the Piedicastello tunnels with three portable scintillator telescopes having different geometrical acceptances. The muon flux measured in the deepest part was found to be about two orders of magnitude lower than the surface flux. This preliminary measurement suggests the use of the site as a facility in which a low environmental background is required.

1. Introduction

In 1936 C. D. Anderson discovered the muon that is the main component of charged cosmic rays at ground. The muon and the electron share the same properties (both are negatively charged leptons) 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 he was informed about 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 particle detector calibrations. However they are also a penetrating background source for many physics experiments and a source of noise 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 muons. For a variety of quantum computing projects, ultra-low level γ-ray spectroscopy [3], ultra-pure material development [4], astroparticle physics [5] and nuclear astrophysics [6], a suppression of the muon flux by a factor 10–100 is usually enough (see e.g. [7–9]). Therefore, in such cases, a laboratory as deep as INFN-LNGS [10] with a million time reduction of the cosmic rays flux is not strictly necessary. For this reason, considering Trento University and INFN-TIFPA are involved in different astroparticle physics and quantum computing projects (see e.g. "Quantum Science and Technology in Trento" [11]), it was considered interesting to measure the cosmogenic background in the tunnels of the Doss Trento hill (see Fig. 1), an easily accessible site with a shielding of ~100 m of rock, recently renovated with waterproofed walls and equipped with electrical power and services.

This preliminary characterization of the muon background in the tunnels of the Doss Trento hill was performed with three different muon telescopes. Moreover, during the measurement campaign there was the opportunity to host some activities of the "Cosmic Box contest" organized by the EEE (Extreme Energy Events) collaboration [12] with educational purposes. In particular, one of the telescopes, the "Cosmic Box" detector, was operated by the students of the Leonardo da Vinci high school of Trento and the measured rates were compared with the data collected by the other two telescopes developed by Trento University and INFN-TIFPA.

2. 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, Italy. 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 Trento was part of an impressive defense system and the Alpini road was 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 to cross 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 "Galleria Nera" (Black Tunnel) and "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) suggests a homogeneous rock density ($\rho \simeq$ 2.7 g/cm^3) with a composition dominated by limestone.

3. Muon flux measurements

Three different telescopes based on plastic scintillators, having different acceptances were used to perform the muon flux measurements inside the Doss Trento hill.

A "Cosmic Box" detector (see Fig. 3 left), referred to as CB detector from now on, made by two layers of 15 × 15 cm^2 plastic scintillator, operating in coincidence at a distance of 19 cm (telescopic configuration) was operated by the students under the supervision of INFN-TIFPA researchers. In 2021 tree identical CB detectors have been used to perform underground muon flux measurements at Nuraxi Figus and Seruci mine in Sardegna, Italy [13]. In the measurement of the underground muon flux in the Doss Trento hill, with the aim to increase the statistics collected by a single CB, two additional muon detectors were built at INFN-TIFPA. One detector, TIFPA0 (see Fig. 3 right) is made by four layers of 25 × 30 cm^2 plastic scintillator working in coincidence. They are superimposed in telescopic configuration with total height of 31 cm. The fourfold coincidence strongly suppress the trigger efficiency of TIFPA0 for low-energy electrons or photons from natural radioactivity as compared with the case of atmospheric muons.

The other detector, TIFPA1, is made by two layers of 25 × 30 cm^2 plastic scintillator, both in coincidence, closely superimposed to allow the maximum geometrical acceptance. The angular field of view of TIFPA0 is similar to the CB one, while the angular field of view of TIFPA1 is almost 2π. All detectors were made by EJ-200 plastic scintillator paddles 1 cm thick. Photosensors used in CB and TIFPA1 were 3 × 3 mm^2 NUV3S-P Silicon PhotoMultipliers (SiPM) by ADVANSID, while four P30CW5 Sens-Tech PhotoMultiplier tubes (25 mm

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 the green dashed line shows the path of the old tunnel crossed by the Alpini road.

diameter) were used in TIFPA0. For all the detectors a coincidence window of ≈100 ns was adopted.

When placed outdoors (200 m a.s.l.) the counting rate of TIFPA0 and TIFPA1 detectors is $\simeq$ 4 Hz while the counting rate of the CB detector is $\simeq$ 0.5 Hz. The background rate of TIFPA0 and TIFPA1 is less than 6×10^{-4} Hz, this limit was inferred by searching for random coincidences between mis-aligned planes with the detectors located in the deepest part of the White tunnel. In particular, when one layer is displaced 30 cm laterally from the telescope, a single muon track cannot trigger the detector. No counts were measured during a 30 min long "background-run" with this configuration.

3.1. Outdoor particle flux measurements

A preliminary outdoor particle flux measurement was performed by TIFPA1 detector, while it was being transported inside a vehicle at different altitudes, h, ascending from Trento (200 m) to Vason (1650 m, green filled points in Fig. 4) and to Forcella Valbona (1775 m, magenta open points in Fig. 4). It is important to note that in this measurement a significant fraction of the counting rate could be attributed to low-energy electrons mainly produced by the muon decay. A linear fit of the counting rate behavior $R(h) = P_0 + P_1(h - h_0)$ where $h_0 = 1$ km, is also plotted as a red line in Fig. 4. Within this linear approximation the parameter $P_0 = 305.6 \pm 1.2$ events/min is the counting rate at 1 km altitude, while $P_1 = 111.4 \pm 1.9$ events/min/km is the average rate variation with the altitude.

The measured counting rate doubles when the detectors are placed at $\simeq$ 2 km of altitude above Trento. The relatively small growth of counting rate with the altitude is very interesting for educational purposes since it is an evidence for the relativistic dilation of muon lifetime. Considering the energy loss and stopping of lower-energy muons, which also play a role, this evidence is further strengthened.

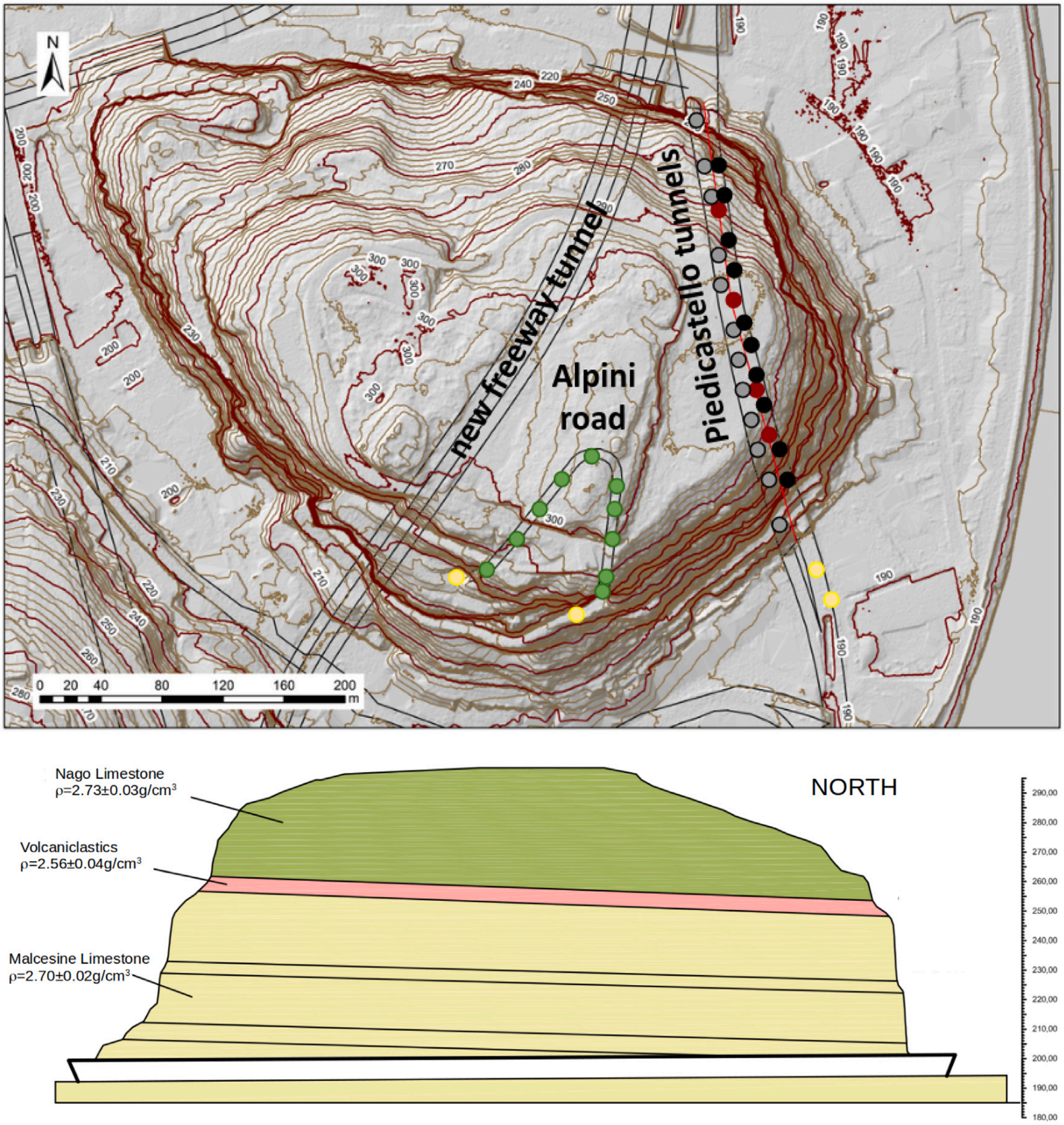

Fig. 2. Topographic map of the Doss Trento hill. The circles depict the sites of muon flux measurement: yellow circles for external measurements, green circles for measurements in the old tunnel of the Alpini road, gray circles for measurements in the White tunnel, black circles for measurements in the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

In particular, it is interesting to compare this result with underground flux measurements, when considering that 2 km of air provides similar column density as 1 m of limestone rock.

This measurement also allows us to check the detector stability (see the inset in Fig. 4). A limit on the systematic uncertainty due to the stability of the muon rate measurements when moving the detector in different locations, is inferred to be below 5%.

3.2. Measurements in the Piedicastello tunnels

The underground muon flux measurements were performed along seven days in the 40 locations reported in Fig. 2. Each day the external counting rates was recorded at the start and at the end of the session to limit the systematic error on the flux ratio evaluations. While in the Black and White tunnels measurements were performed with all detectors, in the Alpini road tunnel only the two (larger) TIFPA detectors were used to accumulate enough statistics in the exposure time compatible with automotive traffic.

Fig. 5 shows the survival probability for vertical muons measured by the TIFPA0 and CB detectors in the Piedicastello tunnels. The overall behaviors are well described by a simple power-law 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 the CB detector is larger due to the smaller detector size. In the central part of both tunnels the vertical muon flux is strongly suppressed down to 0.5% with respect to the flux measured outside.

In Fig. 6 the muon survival probability measured by the TIFPA1 detector is shown. It is important to note that thanks to the wide field of view, the TIFPA1 detector can be triggered by nearly horizontal muons crossing the relatively thin east cliff of the Doss Trento hill. For this

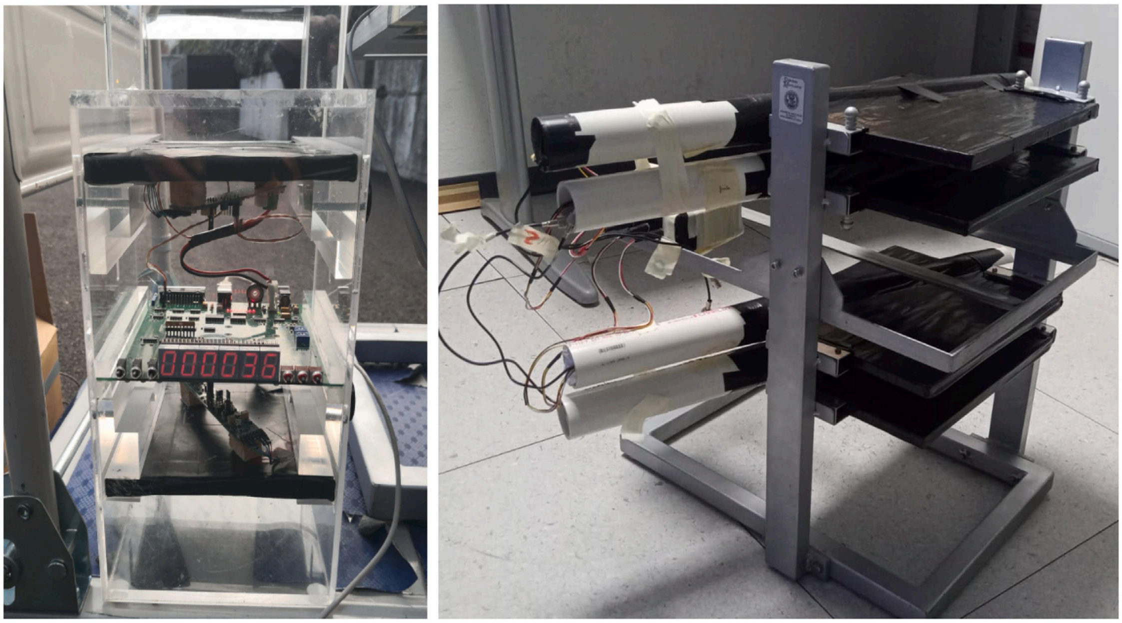

Fig. 3. "Cosmic Box" (CB) detector (left) and TIFPA0 detector (right) .

reason the maximum suppression of the muon flux measured by the TIFPA1 detector is of the order of 1%.

For a similar reason all measurements suggest that a slightly larger shielding is provided by the White tunnel as compared to the Black tunnel. This is even more evident for measurements performed in the north halves of the tunnels where the east wall of the Doss Trento hill is thinner.

To further verify this hypothesis data was collected in the center of the White tunnel by tilting the TIFPA0 detector at 45° and 90° with respect to zenith pointing it towards the four cardinal directions (see Fig. 7). It was found that the measured muon intensity by tilting the detector ∼45° towards the east direction is twice the muon intensity measured with TIFPA0 pointing the zenith and that a sizable fraction of muons is collected by horizontally placing the TIFPA0 detector.

3.3. Measurements in the Alpini road tunnel

The tunnel of the Alpini road is quite narrow (∼4 m) the walls are made of raw limestone and water is dripping from many points of the ceiling. The rock coverage is below 55 m 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 corresponding to a rock thickness in the range 10–50 m.

Each run was limited to 2–3 min to allow cars to pass. Due to the limited exposure, only TIFPAs detectors were used.

In Fig. 8, the muon survival probabilities measured by TIFPA0 and TIFPA1 detectors are shown. For the Alpini road tunnel too, the effect of inclined muon tracks contributing mainly to TIFPA1 triggers is visible. Fig. 9 is obtained combining the vertical muon survival probabilities measured by TIFPA0 detector in the Piedicastello tunnels and in the Alpini road tunnel.

In the same plot the outdoor muon flux measurements reported in Fig. 4 and other underground flux measurements [7,8,13] are also shown for comparison. A single power-law with spectral index $-\frac{3}{2}$ (red line) provides a raw but simple attenuation model in this depth range, better parameterizations of the muon flux are however required when considering muon flux at much larger depths (see e.g. [14]). Vertical attenuation profiles from this power-law model are the ones superimposed as dashed red lines in Figs. 5–8 considering the vertical rock thickness evaluated from the geological section shown in Fig. 2.

4. Conclusions

Measurements of muon flux in the Piedicastello tunnels indicate an attenuation of a factor ∼100 with respect to the outdoor muon flux. When considering the effect of different rock thickness, the flux suppression measured in the Piedicastello tunnels follows the simple behavior suggested by measurements made in other underground sites. In particular at Felsenkeller site a muon flux suppressed by a factor of 40 due to the 45 m thick rock overburden is measured [8], while in the bunker of Soratte mountain a flux that is ∼0.5% of the external one was surviving 200 m of limestone rock [7]. By considering the ease of access of the Piedicastello tunnels site, which requires 15 min 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. As a summary, the proposed location has a sizable reduction of the muon flux while being far more accessible than other locations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

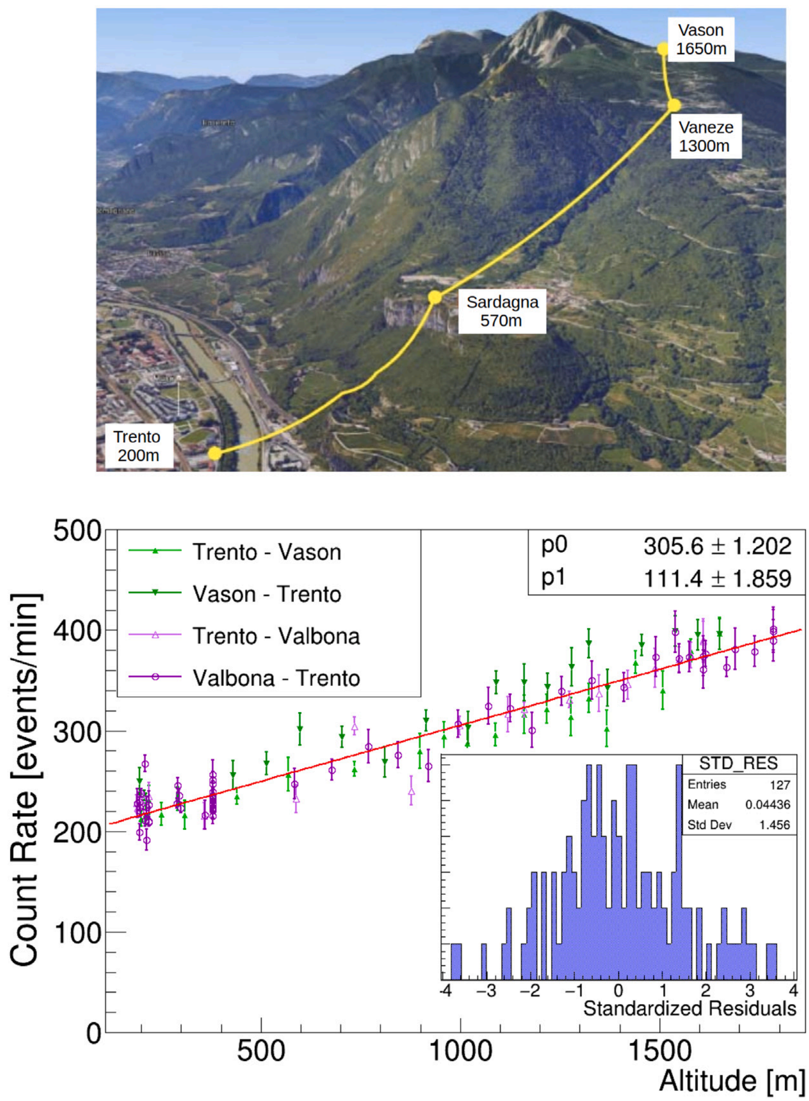

Fig. 4. Outdoor particle flux measurement at different altitudes ascending from Trento (200 m) to Vason (1650 m, green filled points) and to Forcella Valbona (1760 m, violet open points). The lighter shades points were measurements taken uphill while the darker shades points were taken on the way down. Red line is the fit (χ^2/ndf = 2.58) assuming a linear approximation. In the inset the standardized residual distribution useful to test the detector stability.

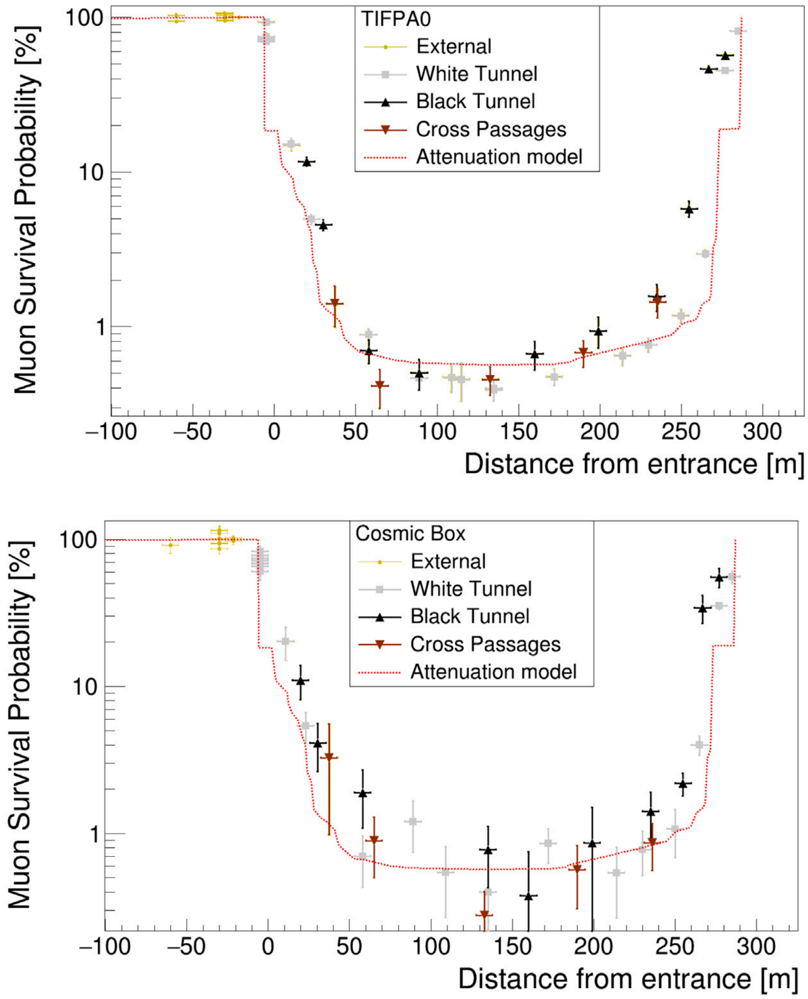

Fig. 5. Survival probability for vertical muons measured by TIFPA0 (top plot) and CB (bottom plot) detectors in the Piedicastello tunnels. The dashed red line shows the muon flux expected by a power-law attenuation model based on the rock profile of Fig. 2.

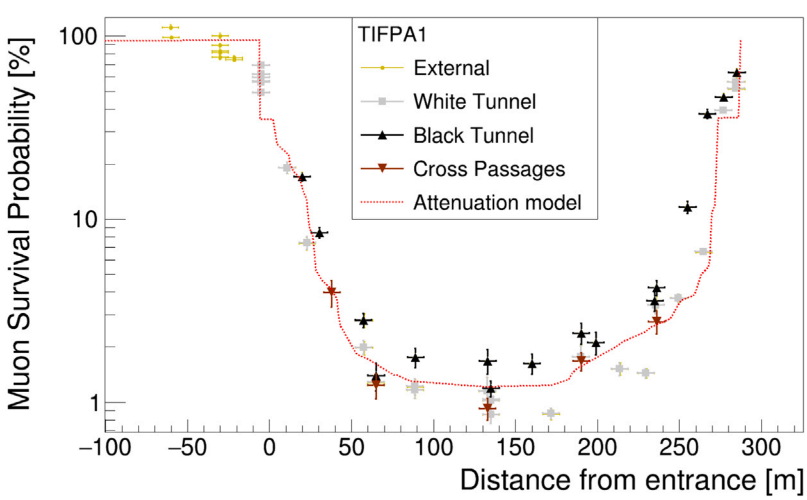

Fig. 6. Muon survival probability measured by the (large field of view) TIFPA1 detector in the Piedicastello tunnels. The dashed red line shows the muon flux expected by a power-law attenuation model based on the rock profile of Fig. 2.

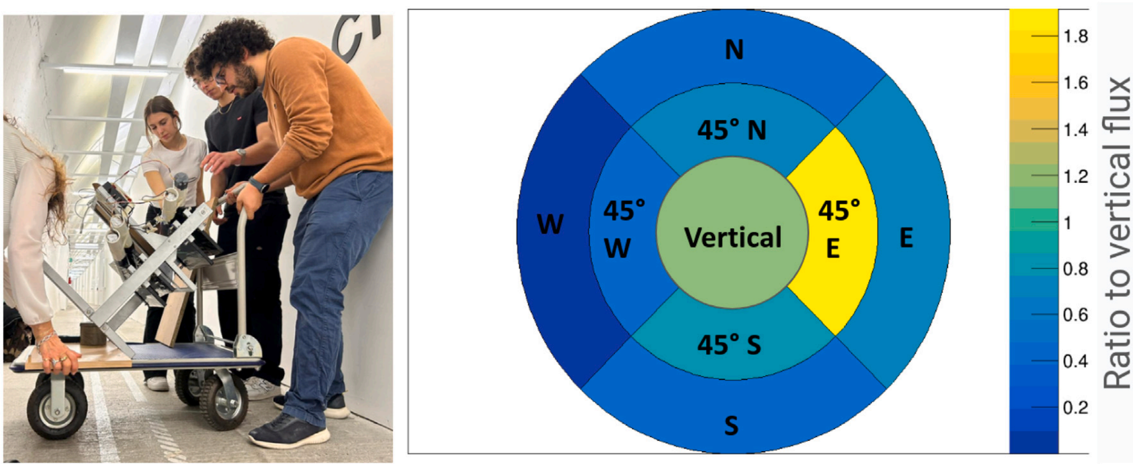

Fig. 7. Measurement of the muon flux angular distribution in the center of the White tunnel with the TIFPA0 detector. Data was collected in the center of the White tunnel by tilting the TIFPA0 detector at 45° and 90° with respect to zenith, pointing it towards the four cardinal directions. The rate measured by tilting the detector ∼45° towards the east direction is twice the vertical one because of the relatively thin east cliff of the Doss Trento hill.

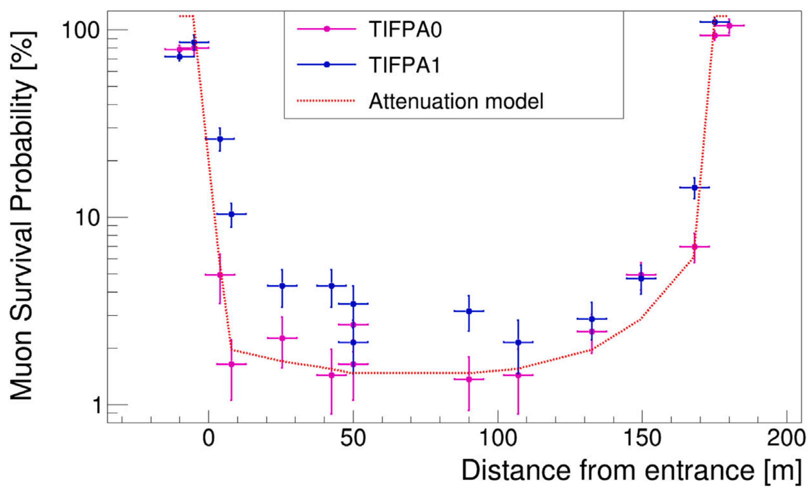

Fig. 8. Measurements of muon survival probabilities in the Alpini road tunnel. The dashed red line shows the vertical muon flux attenuation expected by a power-law model based on the topographic map of the Doss Trento hill (Fig. 2). The effect of inclined muon tracks contributing to the larger rate of TIFPA1 triggers is visible.

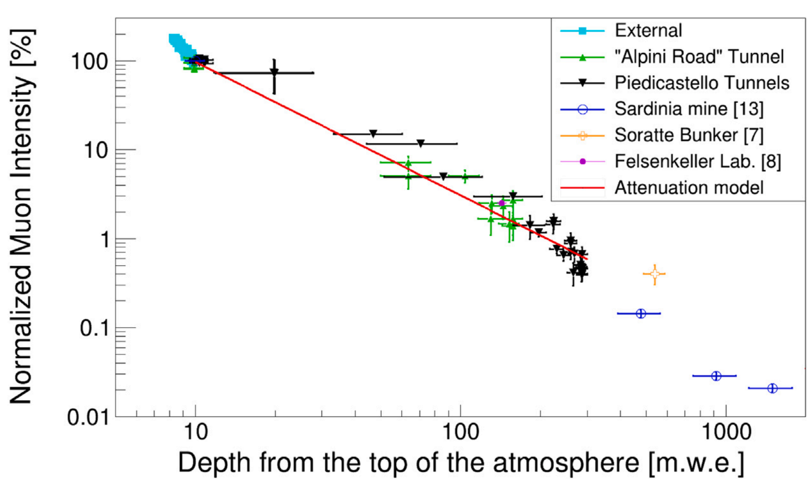

Fig. 9. Normalized muon intensity as a function of the material thickness, h water equivalent, crossed from the top of the atmosphere. Red line is a qualitative attenuation model based on a simple power law $I = [h/(10\text{m.w.e})]^{-3/2}$ to guide the eye.

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