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The underground muon flux with 24 years of data of the LVD detector

C F Vigorito
on behalf of the LVD Collaboration

Dipartimento di Fisica, Universtà di Torino & INFN, via Pietro Giuria 1, 10125 Torino, Italia

E-mail: vigorito@to.infn.it

Abstract.   The Large Volume Detector (LVD), in the INFN Gran Sasso National Laboratory (Italy), has been taking data since June 1992. The experiment, 1 kton of liquid scintillator at the equivalent depth of 3600 m w.e., has been mainly designed to observe low energy neutrinos from the core collapse of a supernova but allows also the measure of the atmospheric muon flux underground as well as the induced neutron production.

In this work we summarize the results of the analysis of the global LVD data set, 5.6 10^7 muons in a livetime of 8402 days collected during 24 years of continuos operations since 1994 up to 2017. The present measurement represents an unprecedented collection obtained by a unique experiment in a fixed location. The modulation in time of the flux and its correlation with the the effective temperature in the upper atmosphere are here discussed.

1. Introduction
The flux of muons detected in underground laboratories is directly related to the production of mesons in the stratosphere by hadronic interactions between cosmic rays and the nuclei of air molecules and to the probability that they decay before interacting. This flux shows time variations which are, at first approximation, seasonal and related to the air density fluctuations affecting the fraction of mesons decaying to high energy muons able to trigger the underground detector. This effect has been known and studied for many decades [1]. Various experiments at Laboratori Nazionali del Gran Sasso (LNGS), Italy [2, 3, 4, 5], and in other underground sites [6, 7, 8, 9, 10, 11, 12, 13, 14] were able to measure the muon flux underground and its variations on a time scale of few years at different depths. In this work we present the results of the monitoring of the muon flux by LVD, the largest dataset ever provided so far for undeground muons by a single detector.

2. Temperature effects on the muon rate
The variations of the temperature in the stratosphere causes variations in the air density, changing the probability that the mesons, produced by primary cosmic rays interactions, could interact or decay to high energy muons. In particular, an increase in the temperature of the stratosphere induces a decrease in air density, thus reducing the chance of meson interaction, which in turn results in a larger fraction decaying to produce high energy muons which can eventually reach underground sites. Deviations from the average muon flux measured underground, $\Delta I_\mu(t) = (I_\mu(t) - I_\mu^0)$, can be correlated to variations of the average atmospheric

temperature $\Delta T(X) = (T(X) - T^0(X))$ at a given depth (altitude) X. The net effect can be written as: $\Delta I_\mu(t) = \int dX \ W(X) \cdot \Delta T(X, t)$ where the weight $W(X)$ (see [15] for details on calculation) reflects the altitude dependence of the production of mesons in the atmosphere (and their decay into muons that can be observed deep underground) and the integral extends over the full atmospheric depth.

Assuming the atmosphere as a stratification of N layers with a continuos distribution of temperature and pressure is possible to define an effective temperature, T_{eff} defined as the weighted average over the atmospheric depth:

$$T_{eff} = \frac{\int dX \ T(X)W(X)}{\int dX \ W(X)} \simeq \frac{\Sigma_{n=0}^N \Delta X_n T(X_n) W(X_n)}{\Sigma_{n=0}^N \Delta X_n W(X_n)} \tag{1}$$

being the temperature profile measured at N discrete atmospheric levels, X_n. Figure 1 shows the average temperature profile for the period [1994-2017] at LNGS site and the corresponding weight $W(X)$ as function of the pressure levels X_n. Defining the effective temperature coefficient as $\alpha_T = \frac{T_{eff}}{I_\mu^0} \int dX \ W(X)$, the relation between effective temperature and muon intensity variations can be simplified as: $\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}}$.
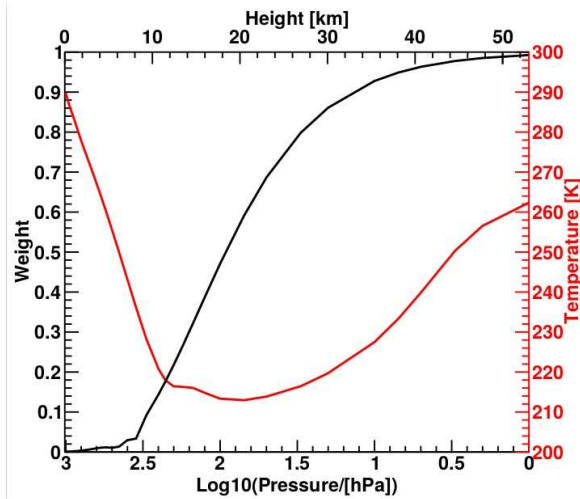

Figure 1. Distribution of the average [1994-2017] temperature profile at LNGS site (red line) and the calculated weight $W(X)$ (black line) as a function of the atmospheric depth X [hPa] or altitude [km]).
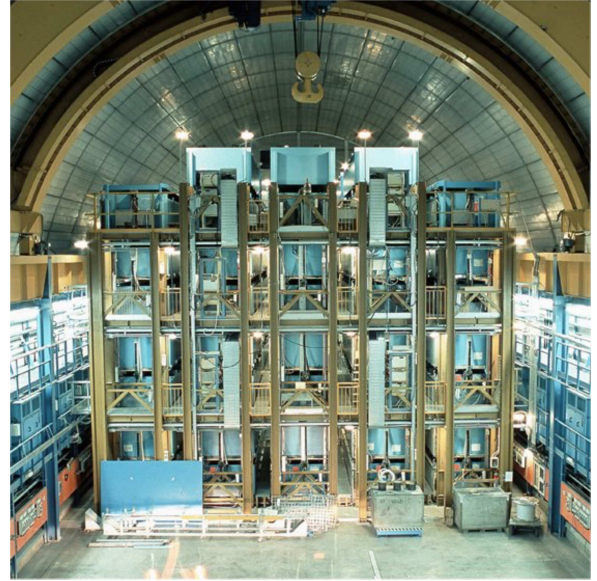
Figure 2. Front view of the LVD experiment in the hall A of the Laboratori Nazionali del Gran Sasso (Italy).

3. The LVD detector

LVD (see figure 2) is a 1000 t liquid scintillator experiment aimed at detecting neutrinos of astrophysical origin. It consists of an array of 840 scintillator self-triggering counters, 1.5 m^3 each, viewed from the top by three photomultipliers (PMTs). The counters are organized in a modular and compact geometry which allows to achieve a very high duty cycle. This feature is essential for the search of unpredictable sporadic events like neutrino bursts from Gravitational Stellar Collapses and it is valuable for the study of time variations of the muon flux underground. LVD has been in operation since 1992, June 9th after a short commissioning phase, its mass
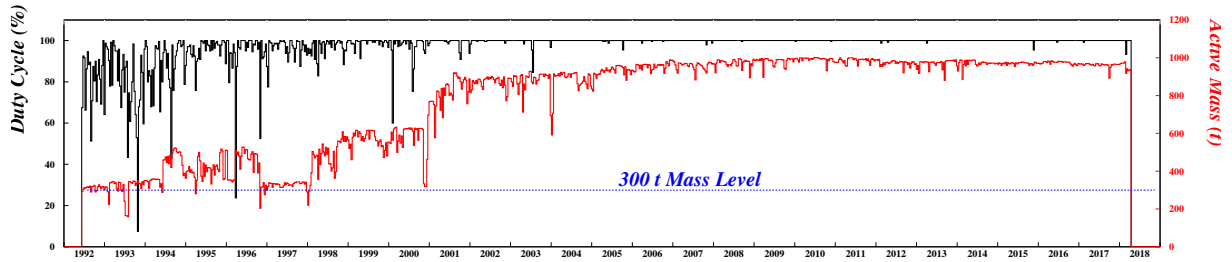
Figure 3. LVD duty cycle(black line) and active mass(red line) as a function of time from 1992, June 9th 1992 to 2017, May 28th.

increasing from 300 t to its final one, 1000 t, in January 2001. The LVD active mass and duty cycle evolution in time, updated to May 2018, are shown in figure 3. The LVD trigger logic (extensively described in [16]) is based on the 3-fold coincidence of the PMTs in a single counter corresponding to an energy threshold $E_{th} \sim 4\,\mathrm{MeV}$. The energy resolution of the counter is $\Delta E/E \sim 15\%$ at 10 MeV. The time stamp of triggered events has a relative time precision of 12.5 ns with an absolute accuracy of 100 ns.

For the purpose of this analysis, data collected in years 1992 and 1993 have been discarded because of scarce of contiguity and low duty cycle efficiency, both correlated to the deployment phases of the first part of the detector.

4. Temperature data

The temperature data has been obtained from the European Center for Medium-range Weather Forecasts (ECMWF ERA-Interim data) [17]. It exploits different type of observations (e.g. surface, satellite, and upper air sounding) at many locations, and then uses a global atmospheric model to interpolate them to a particular location. We considered in this analysis the precise coordinates of the LNGS underground halls (13.5333°E, 42.4275°N) to download data from the ECMWF grid at the highest possible resolution. The model provides atmospheric temperatures at 37 discrete pressure levels in the [1-1000] hPa range, four times a day at 00.00 h, 06.00 h, 12.00 h, and 18.00 h UTC. Based on this data set, the T_{eff} is calculated following equation 1 four times a day providing a mean daily value. The variance of the four daily values is assumed as estimate of the uncertainty of the mean. The daily value of T_{eff}, over the period considered in the present analysis, is shown in figure 4: the simple average gives $< T_{eff}^o >= (220.307 \pm 0.006)\,\mathrm{K}$.

5. LVD muon data

Muons are identified in LVD through the time coincidence of signals with an energy release $E \geq 10$ MeV in two or more counters within a time window of 175 ns, which is large enough to include the time jitter of the PMT's transit time. Data selection is performed via the standard quality cuts that have been defined in the search for neutrino burst [18]. Additionally, the muon-like events associated to the CNGS (CERN Neutrino to Gran Sasso [19]) neutrino beam in the period [2006-2012] have been excluded if in coincidence with the time of the beam spills inside a time window of $[-10, +20.5]\mu s$, being $10.5\mu s$ the spill duration. The resulting dataset consists of $5.6 \cdot 10^7$ muons for a total livetime of 8402 days. The measured daily muon rate is shown in figure 5 (pannel top figure) and it is mainly affected by the different detector configurations over the time, as shown in figure 3. The muon flux underground $I_\mu(t)$ is then obtained through the ratio between the measured daily muon rate and the simulated detector exposure (i.e the geometrical acceptance times the livetime) which changes according to the LVD active mass configurations
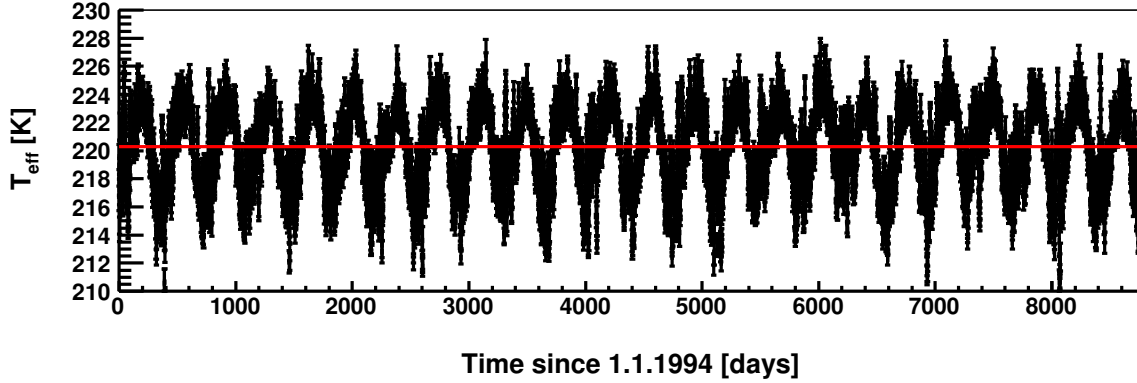
Figure 4. Mean daily values of T_{eff} from 1994 up to 2017 as obtained by using ECMWF Era-interim data: error bars account for the RMS dispersion in each single day. The red line is the overall average value.

and duty cycle as shown in figure 3. A detailed description of the simulation can be found in [20]. For the full detector configuration (i.e. $M = 1000$ t) the geometrical acceptance, averaged over the cosmic muon arrival directions in the hall A of LNGS, corresponds to $S = (298 \pm 3)\,\mathrm{m}^2$, where the uncertainty (1%) is mainly dominated by the systematic errors assumed in the muon direction. The obtained daily detector exposure and the muon flux are shown in figure 5 (pannel middle and bottom figures) . The bigger fluctuations which are observed till the beginning of 2001 (day 2557) are due to the lower active mass of the detector during construction phase. The average value of the muon flux is $I_\mu^0 = (3.35 \pm 0.0005^{stat} \pm 0.03^{sys}) \cdot 10^{-4}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$, being the systematic error induced by the geometrical acceptance calculation.

6. Results

As a first approximation, the daily muon flux has been fitted with a sinusoidal function $I_\mu(t) = I_\mu^0 + \Delta I_\mu cos(\frac{2\pi}{T}(t - \phi))$ obtaining a period of $T_\mu = (365.1 \pm 0.2)\,\mathrm{d}$, which is compatible with what expected and also measured, in same way, in the effective temperature modulation $T_{T_{eff}} = (365.1 \pm 0.3)\,\mathrm{d}$. The amplitude ΔI_μ of the muon flux and the mean phase ϕ of the modulation are therefore better evaluated fixing $T = 365.25$ d, and including systematic errors of the measured daily values. We obtained $\Delta I_\mu = (4.7 \pm 0.3) \cdot 10^{-6}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$ $(\Delta I_\mu/I_\mu^0 \sim 1.4\%)$ and a phase $\phi = (183 \pm 1)\,\mathrm{d}$ (corresponding to the beginning of July).

From the daily muon flux (as in figure 5) and effective temperature (as in figure 4) the scatter plot of the relative daily variations values $\frac{\Delta I_\mu}{I_\mu^0}$ and $\frac{\Delta T_{eff}}{T_{eff}^0}$ are obtained, as shown in figure 6. The value of α_T is obtained performing a linear regression which accounts for error bars of both parameters. We got a value of $\alpha_T = 0.94 \pm 0.02$ (correlation coefficient $r = 0.56$), which is in agreement with the expected value of $\alpha_{T,LNGS} = 0.92 \pm 0.02$ at LNGS depth [6, 15]. This result confirms the values that were also measured by other detectors at LNGS.

Figure 7 shows a collection of the α_T values by various experiments at different depths, together with the expected theoretical prediction including muon production by both pions and kaons.
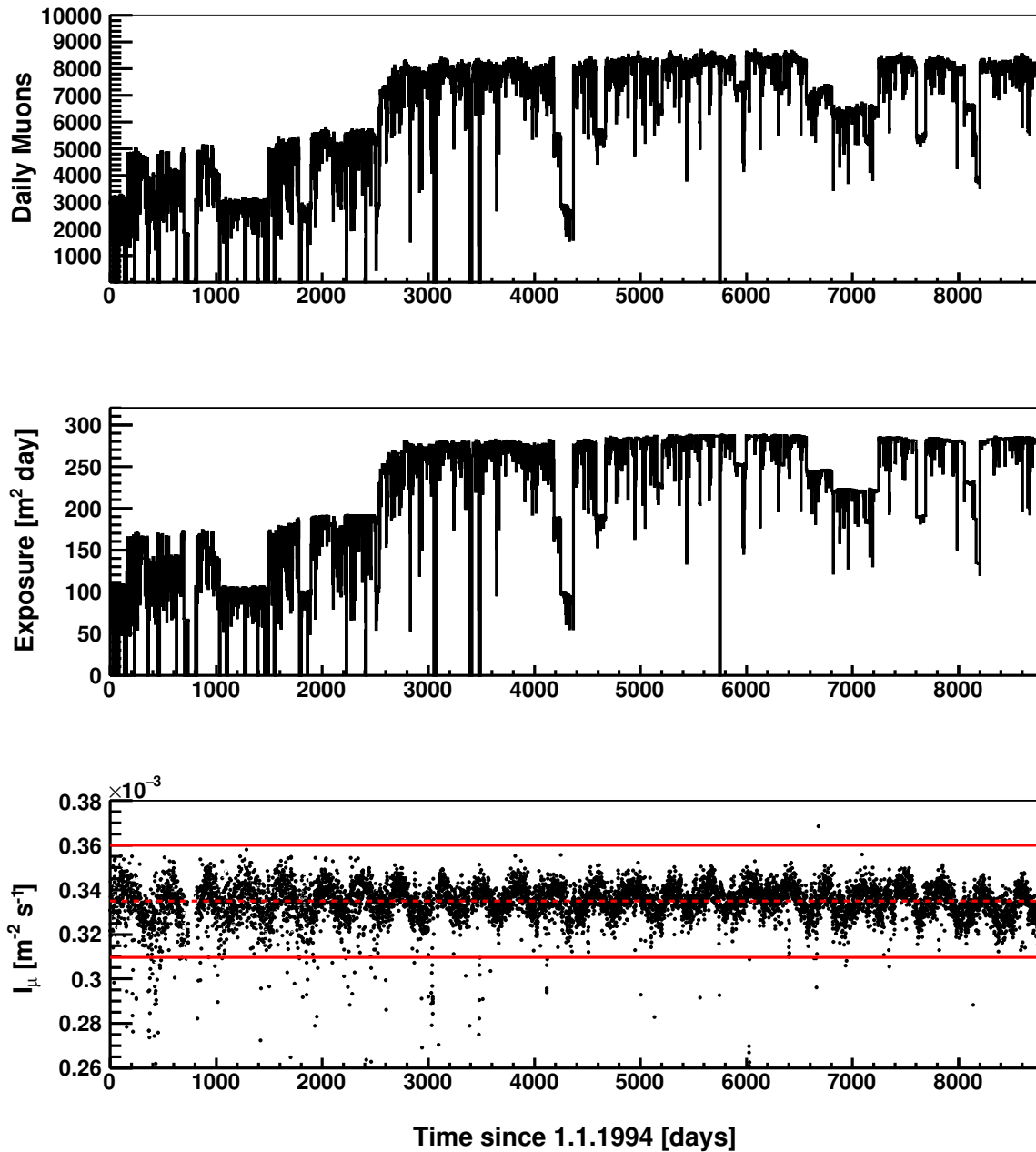
Figure 5. From top to bottom: daily muon rate, exposure and flux from 1994 up to 2017. The bigger fluctuations in the flux, observed till the beginning of 2001, are due to the lower active mass of the detector during construction.

7. Conclusions

We have analized 5.6×10^7 muon events detected by the LVD experiment over 8402 live days in the [1994-2017] period to search for variations of the muon flux underground in correlation with the atmospheric effective temperature variations at LNGS site.

The average value of the muon flux over 24 years of data is: $I_\mu^0 = (3.3335 \pm 0.002[stat.] \pm 0.03[sys])10^{-4}\mathrm{m}^{-2}\mathrm{s}^{-1}$, being the error dominated by the sistematic uncertainty on the geometrical acceptance correction (1%). A clear modulation with a time period $T = 1\,\mathrm{y}$ is observed with an amplitude of 1.4% and an average phase corresponding to beginning of July. Relative variations of the muon flux and of the effective temperature are correlated: the measured coef-
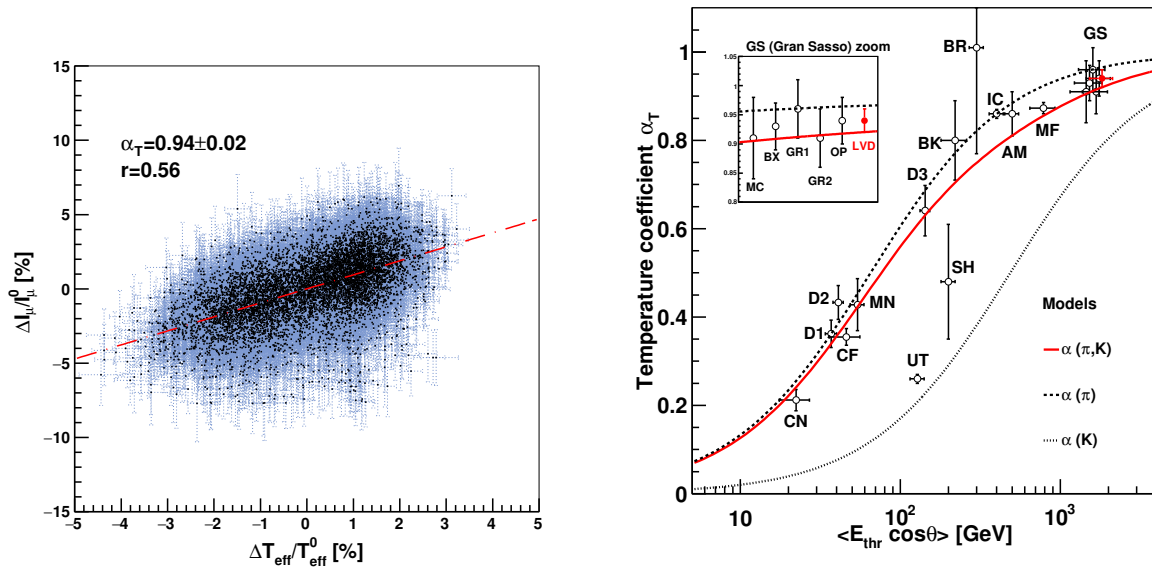
Figure 6. Scatter plot of daily values of $\Delta I_\mu/I_\mu^0$ and $\Delta T_{eff}/T_{eff}^0$: the dashed red line corresponds to the linear regression of the whole data set. The value of the Pearson coefficient R=0.56, being the DoF=8400, excludes the chance probability of a random correlation.

Figure 7. Measured values for the effective temperature coefficient α_T at different site depths. The results of this analysis (in red) compared with those of other detectors (see text for details & references). The red line is the predicted value including both muon production by pions and kaons, shown separately by the dashed lines (see [6] for details).

ficient $\alpha_T = (0.94 \pm 0.02)$ is well in agreement with previous measurements at LNGS site and also with the expected value for the LNGS depth.

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