Analysis of the seasonal modulation of the cosmic muon flux in the LVD detector during 2001-2008.

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Abstract. **The Large Volume Detector (LVD) is a 1 kt liquid scintillator detector whose major purpose is the study of neutrino bursts from gravitational stellar collapses. The experiment, taking data since 1992 in the INFN Gran Sasso National Laboratory, Italy (LNGS), at the average depth of 3600 m w. e., is also well suited for the study of penetrating cosmic muons (E_μ at the surface > 1.3 TeV). In this paper we analyze 8 years of data (2001-2008) to study the seasonal modulation of the muon flux. We find a modulation with period 1 year; on average the amplitude is 1.5%, with the maximum intensity in July, in agreement with theoretical expectations and previous measurement at LNGS.**

Keywords: **Cosmic muons, underground experiment, seasonal modulation.**

I. INTRODUCTION

The Large Volume Detector (LVD[1]), in the INFN Gran Sasso National Laboratory, Italy (LNGS), at the average depth of 3600 m w. e., is a 1 kt liquid scintillator detector whose major purpose is the study of neutrino bursts from gravitational stellar collapses [1]. The experiment is in data acquisition since 1992 and it reached its final configuration at the end of 2000. LVD is also well suited for the study of penetrating cosmic muons (E_μ at the surface > 1.3 TeV) [2].

Underground muons originate primarily from the decay of mesons produced in high energy interactions between primary cosmic ray particles and atmospheric nuclei. As described in [3] and [4], the flux of cosmic muons underground is related to the temperature of the Earth atmosphere. The dependence of muon intensity variations on the atmospheric temperature is expressed phenomenologically as:

$$\frac{\Delta I_\mu}{I_\mu^0} = \int_0^\infty dX \; \alpha(X) \; \frac{\Delta T(X)}{T(X)} \qquad (1)$$

where $I_\mu^0 = I_\mu(T_0, E > E_{thr})$ is the differential muon intensity integrated from the energy threshold ($E_{thr} \sim 1.3$ TeV) to infinity, assuming the atmosphere is isothermal at temperature T_0, and ΔI_μ are fluctuations about I_μ; $\alpha(X)$ is the 'temperature coefficient' that relates fluctuations in the atmospheric temperature at depth X ($\Delta T(X)/T(X)$) to the fluctuations in the

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integral muon intensity; the integral extends over atmospheric depth from the altitude of muon production to the ground. For deep sites there is a positive correlation between the underground muon intensity and the atmospheric temperature (the higher the temperature, the higher the muon flux underground) because, as the atmospheric temperature increases, the density of the air decreases and fractionally more pions/kaons decay to muons before interacting. Typically, in the boreal hemisphere, the muon flux reach the maximum in July and the minimum in January.

This effect has been previously measured by various experiments deep underground: MACRO [5], AMANDA [6] and MINOS [7]: however their data cover respectively 4, 1 and 3 years. In this paper we study the seasonal modulations by analyzing 8 years of LVD data between 2001 and 2008.

II. DETECTOR DESCRIPTION

The LVD detector is made by 840 scintillation counters (1.5 m^3 each) arranged in a modular structure: 8 counters are assembled in a module called 'portatank'; 35 portatanks (5 columns × 7 levels) form a 'tower'; the whole detector is made by three identical towers. See figure 1 for a schematic view of the detector. The external dimensions of the active volume are $13 \times 23 \times 10$ m^3.

Each counter is viewed from the top by three photomultipliers, and it is self-triggered at the energy threshold $E_{th} \simeq 4$ MeV; then the sum of the PMT signals is sent to the a TDC-ADC module, recording the energy with a resolution $\sigma_E/E = 7\% + 23\%/\sqrt{E}$ and the relative time of the events with a 12.5 ns accuracy. The absolute time of each event is obtained with three slave clocks connected with the GPS master clock in the outside laboratory, with a 100 ns overall accuracy.

The data collected by the DAQ system are divided into runs; a new run starts either after 12 hours of data taking either when there are modifications in the configuration of the apparatus (e. g. if a portatank or a tower are switched off for maintenance).

III. DATA ANALYSIS

We analyzed the whole available data set with the detector in its final configuration, starting in January 2001 and ending in December 2008; the total livetime is 2907 days (99.5% of 8 full years, i. e. 2922 days).

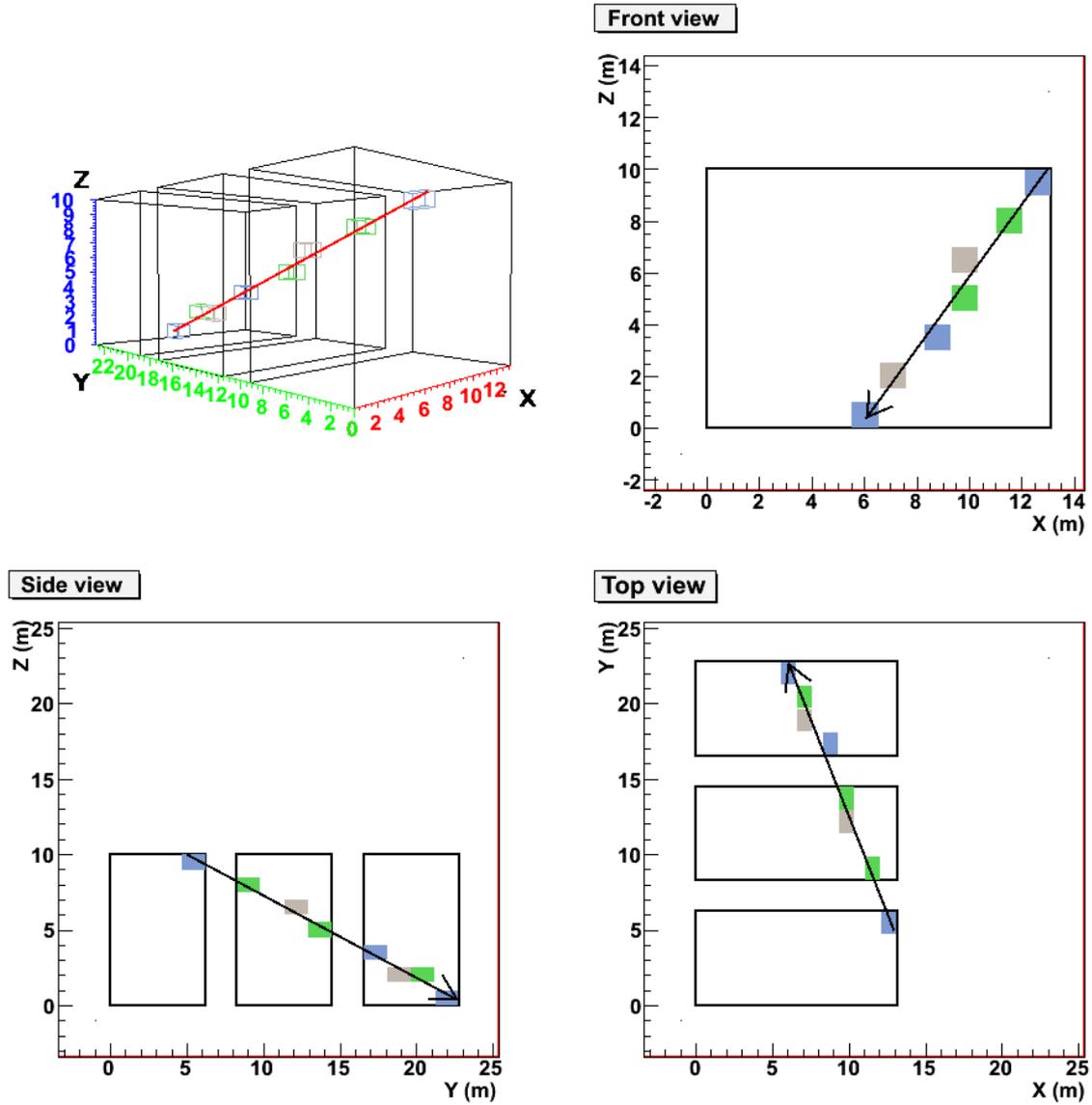A typical muon event in LVD, as the one shown in figure 1, crosses many counters and releases few

Fig. 1. Schematic view of the LVD detector: the black empty boxes delimit the three LVD towers. The X (Y) axis is orthogonal (longitudinal) to the main axis of the LNGS hall, while the Z axis is vertical. This event display represents a single muon crossing 8 counters (the full rectangles). The black arrow is the result of a linear fit to the center of the crossed counters.

hundreds of MeV in each one (the most probable energy loss by muons in each counter is 170 MeV); moreover the time difference between two counters crossed by a muon is of the order of tens of ns.

In the raw data, for each event, there is the information of the number of crossed counters N_c together with their associated time t_i and energy E_i. An event is selected as 'muon candidate' if there are at least 2 distinct counters with $E_i > 10$ MeV and time difference $\Delta t < 250$ ns. We build, for each run, the database with the relevant information of the 840 scintillation counters; they are labeled as:

- OFF, if not present in any 'muon candidate',
- HIGH frequency, if their rate in 'muon candidate' $R_i > 3 \cdot 10^{-3}$ Hz (being the average rate per counter $7 \cdot 10^{-4}$ Hz),

- BAD-TDC if there are known TDC problems for that counter.

Finally we look for genuine muons requiring that the (at least) two counters that trigger a muon event are not part of the HIGH or BAD-TDC sample.

Note that, with these selection cuts we are accepting events with at least one muon track, without any requirement on the muon multiplicity inside the events; thus, among the selected sample there are single muons, multiple muons and muons accompanied by an e.m. or hadronic cascade. In this analysis, we count the 'muon events' rather than the muon tracks. We also point out that, given the detector structure and the simplicity of the selection cuts, we can reconstruct events coming from any direction, including horizontal tracks; the upper hemisphere is thus fully covered ($\Omega = 2\pi$).
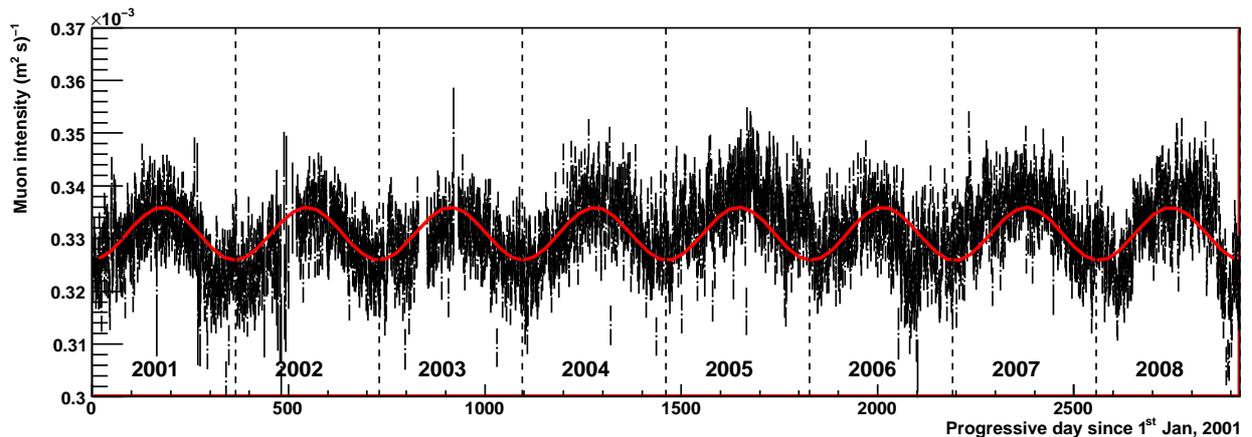
Fig. 2.   Muon intensity along the 8 years of data acquisition. Each bin corresponds to one day, starting from 1st January, 2001 to 31st December, 2008. The error bars are the statistical uncertainty. The solid red curve is the result of a cosinusoidal fit to the data in the form shown in eq. 3 The vertical dashed lines separate each solar year.

Since the configuration of the apparatus may be changed run by run in terms of number and position of the active counters, and since the rate of the detected muons depends critically on the active counter configuration, we developed a Monte Carlo simulation to take into account the acceptance and the efficiency of the detector in detecting muons. The geometry of the LVD detector has been described in detail through the GEANT4 [8] program. The distribution of the muon energy and arrival direction has been generated accordingly to the MUSUN code [9], developed for the Gran Sasso rock distribution around the LNGS. The muons are sampled uniformly in a circle orthogonal to the chosen direction and tracked trough the LVD detector: the information on the number of crossed counters, together with the time and energy in each counter, are stored; then we apply the same selection cuts as we did in the real data.

With all the scintillation counters considered as active, we derive the geometrical acceptance (averaged over the cosmic muon arrival directions in the LNGS) $A = (298 \pm 3)$ m^2, where the uncertainty (1%) is mainly dominated by the systematic errors assumed in the muon direction given by the MUSUN code. Since the number and also the position of the counters that do not participate to the muon trigger change run by run, we generate 10^5 muons for each run, removing from the MC the corresponding OFF, HIGH and BAD-TDC counters. We calculate the muon detection efficiency ϵ defined as the ratio between the number of detected muons in each configuration and the one with the fully active detector.

The last phase of the muon event selection consists in applying quality cuts to the data taking itself: runs lasting less than one hour, or with $\epsilon < 0.5$, or with more than 10 anomalous TDC counters, are not considered in the analysis. The fraction of lost time is negligible (7%), moreover the runs removed from the analysis are spread all over the whole period of data acquisition; indeed the largest continuous amount of dead time is 10 days.
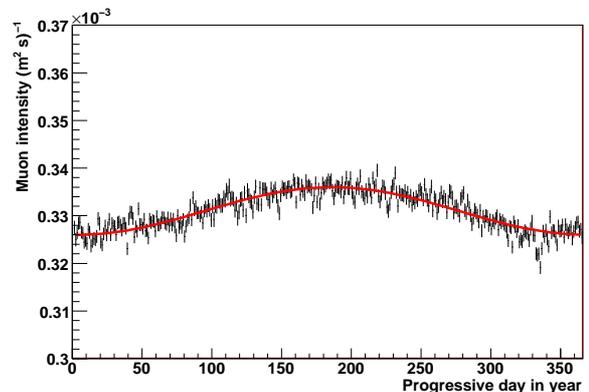

Fig. 3.   Superposition of the mean daily intensity for the averaged total data set 2001-2008 into one year.

The total analyzed live time results 2724 days. In normal conditions (three active LVD towers) the number of detected muons per day is of the order of ~ 8000 (~ 0.1 Hz). The total number of muons in the full data set 2001-2008 is about 21.5 millions.

IV. RESULTS

The muon intensity in the i-th run is now defined as:

$$I_i^\mu = \frac{N_i^\mu}{A \cdot \epsilon_i \cdot t_i} \qquad (2)$$

where N_i^μ is the number of detected muon events, A is the geometric acceptance, t_i and ϵ_i are, respectively, the duration and the detection efficiency of each run.

The muon intensity measured day by day since 2001 till 2008 is shown in figure 2. A modulation is clearly visible; fitting the distribution with the following function:

$$I^\mu = I_0^\mu + \delta I^\mu \; \cos\left(\frac{2\pi}{T}(t - t_0)\right) \qquad (3)$$

we obtain an average intensity $I_0^\mu = (3.31 \pm 0.03) \; 10^{-4} \; (m^2 \; s)^{-1}$ and a period $T = (367 \pm 15)$ days, i. e. compatible with one year.

The amplitude of the modulation δI^μ and the phase t_0 are better evaluated projecting and averaging the results of the eight years of analysis into one single year, as shown in figure 3. We obtain, fitting again with equation 3 but with fixed period $T = 1$ year, $\delta I^\mu = (5.0 \pm 0.2) \; 10^{-6} \; (\mathrm{m}^2 \; \mathrm{s})^{-1}$, corresponding to 1.5%. The obtained phase is $t_0 = (185 \pm 15)$ days, corresponding to a maximum intensity at the beginning of July, while the minimum is at the beginning of January; the χ^2/d.o.f. is 577/362.

The statistical significance of the observed modulation is estimated grouping the data set in bins large 7 days (the statistical error in each bin is therefore $\sim 0.4\%$); in January and July (that is, at maximum) the deviation from the average value is larger than 5 σ.

V. Conclusions

We have analyzed $21.5 \; 10^6$ muon events detected by the LVD experiment over 2724 live days during 2001-2008 to search for a seasonal modulations of the cosmic muon flux ($E_\mu > 1.3$ TeV).

The average value of the 'muon events' flux over the 8 years of analyzed data is

$$I_0^\mu = (3.31 \pm 0.03) \; 10^{-4} \; (\mathrm{m}^2 \; \mathrm{s})^{-1}$$

in good agreement with previous measurements at LNGS [2]. The uncertainty is dominated by the systematic error assumed on the acceptance correction (1%), while the statistical error is negligible (0.02%).

We find that a modulation is clearly seen, with a time period of 1 year and an averaged amplitude of 1.5 %; the maximum of the muon intensity is, on average, at the beginning of July and the minimum at the beginning of January. The statistical significance of the observed modulation is larger than 5 σ at the maximum deviations from the average value.

An analysis of the direct correlation of the daily muon intensity in LVD with the atmosphere temperature to calculate the α coefficient in equation 1 is ongoing and will be presented in a separate work.

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Appendix A: OPERA-LVD coincidences

We attempted a first search of coincident events between the OPERA and LVD detectors (see also [10] in these proceedings). The relative position of the two detectors, both at LNGS, and separated by an average distance of $\sim$170 m, allows an unprecedented analysis of very large cosmic ray showers looking at their penetrating TeV component. The physics case follows the consideration that TeV muons separated by hundreds of meters are produced in high p_T interactions up in the atmosphere ($p_T > 3$ GeV/c) where perturbative QCD can be applied. One can therefore relieve the interpretation of cosmic ray data from the phenomenological models usually adopted to describe the bulk of soft processes occurring in cosmic ray showers.

We analyzed data of 2008, during the long run of the 'CERN Neutrinos to Gran Sasso' (CNGS) beam, for a total livetime - in common between the two experiments - of 131.3 days. In a time-window of 15 μs we found 145 events on-time with CNGS (beam events) and 38 events out of the CNGS spill window (cosmic events). The first sample of events have a time difference within the 10.5 μs of the CNGS spill width and is well centered around zero, probing the good inter-calibration accuracy of the detector timing systems.

The cosmic ray sample, on the other hand, has a narrow distribution peaked at -573.4 ns with an RMS of 94 ns. The central value of the distribution has a simple interpretation: the coincident events detected up to now are not multiple muons (one per each detector), but single muon events entering horizontally from the OPERA side sticking the LVD detector after 573.4 s of flight (corresponding to 172 m). Indeed, the OPERA-LVD direction lies along the so-called "Teramo valley", where the mountain profile exhibits a small rock depth even for horizontal directions. Visual inspection using the event displays of both the experiments confirms this conclusion.

This analysis will be extended with the statistics accumulated in the forthcoming runs in order to improve the limits on high p_T events.

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