LVD status report: underground muon physics

N Agafonova on behalf of the LVD Collaboration
Institute for Nuclear Research RAS, 117312, prospect 60-letiya Oktyabrya, 7a, Moscow, Russia
E-mail: agafonova@inr.ru

Abstract. The scintillation LVD detector is used to study cosmic ray muons with mean energy of 280 GeV at an average depth of 3.6 km w.e. The experiment has been going on since 1992 at the Gran Sasso underground laboratory, Italy. During 28 years of work, the characteristics of the muon flux, its dependence on depth and seasonal variations and, the charge muon ratio, the multiplicity curve of muon groups and the decoherent curve have been obtained.

1. Introduction
Research in the field of neutrino astrophysics, neutrino physics, search for rare processes predicted by theory requires the creation of low-background underground laboratories. Apart from the natural radioactivity of rocks and materials of setups, the main means of intractable background underground are cosmic ray muons. Muons, passing through the rock and the matter of the detectors, lose their energy for ionization, for the emission of bremsstrahlung γ-quanta, the production of electron-positron pairs, and deep inelastic interaction.

The LVD (Large Volume Detector), located underground, can measure atmospheric muon intensities from 3000 to 12 000 hg/cm$^2$ and higher (which corresponds to muon energies at sea level from 1.3 to 40 TeV) at zenith angles from $0^\circ$ to $90^\circ$. This allows us to study muon spectra and their characteristics at energies 1.3−40 TeV, which correspond to energies of primaries of about 10−400 TeV. Here we briefly present the results of the LVD experiment over the past 10 years of muon analysis underground.

2. LVD description
The main task of the LVD experiment is a long-term search for neutrino bursts from gravitational collapses of stellar cores [1]. Due to its design features, the detector also has ample opportunities for studying cosmic ray muons underground.

The detector is located at a depth of $\langle H \rangle = 3650$ m w.e. The average energy of the muon flux is $\langle E_\mu \rangle = 280$ GeV, the vertical intensity of the muons is about $3.3 \times 10^{-4}$ m$^{-2}$ s$^{-1}$. LVD consists of 3 towers, each of which contains five vertical columns. The column, of seven levels, includes portatanks, each containing eight scintillation counters. The complete LVD setup contains 840 scintillation counters. The first LVD tower began operation in 1992, 3 towers in 2002 [2], [3].

The total mass of the liquid scintillator is 970 tons. The mass of iron forming the supporting structure of the installation is about 1000 tons. The LVD includes a track system, which was used to determine the characteristics of muon events: the direction of the muon trajectory, the multiplicity of muon groups, and the decoherence curve. The track system consists of vertical and horizontal planes of gas discharge tubes operating in a limited streamer mode. The accuracy

[1] Reference for the first reference
[2] Reference for the second reference
[3] Reference for the third reference
of determining the coordinates of the track of a charged particle is ±3 cm. It is determined by
the width of the strips of the planes of the track system (2 cm) and their spatial arrangement
relative to each other.

The main element of the detecting system is a scintillation counter with a volume of 1.5 m³. The
rectangular shape of the counter, its dimensions 1.0×1.0×1.5 m³, the material, the number and
location of photomultiplier tubes (3 photomultipliers on the upper edge of the counter), as
well as their parameters (diameter, photocathode, gain) were dictated by the conditions of the
planned experiments.

An LVD event is a sequence of pulses from more than 2 scintillation counters for 1 ms and
also includes information from the track system. Muon events are selected from among all LVD
events in accordance with the developed selection criteria. The goal of the selection procedure
is to isolate a muon event and determine its type: a single muon, a group of muons and its
multiplicity, a muon or a group of muons accompanied by a shower.

3. Selected results
We have reconstructed muon events detected during the operation of the track system in
the setup. With the simultaneous operation of two LVD towers (560 scintillation counters), 2 155844
single muons and 112145 muon groups with multiplicity from 2 to 27 were obtained. For these
muons, the following were determined: a) the distribution of events over the muon multiplicity, b)
the decoherence curve, i.e. the distribution of possible combinations of muon pairs in multiple
events versus the distance between muons in a pair, c) the angular dependence of the muon
intensity [4].

The spectrum of multiplicities and the decoherence curve were used to study the chemical
composition of primary cosmic rays (PCR) in the energy range >3×10¹⁵ eV. Comparison of
experimental distributions with simulation results indicates an increase in PCR weight. The
distribution of muon events by multiplicity is necessary in determining the specific yield of
neutrons generated by muons in the substance of the LVD detector, as well as in determining
the multiplicity of neutrons from µ-Fe -captures.

The angular distribution of muons allows one to obtain the dependence of the intensity of
muons on the depth [5]. The maximum depth from which atmospheric muons can be detected is
12 km w.e. The analysis of the ”depth–vertical-intensity” relation allowed us to derive the power
index γ of the primary all-nucleon spectrum: γ=2.78±0.05. In addition, the muon intensity and
the angle for the maximum muon intensity of about 28° are used to determine the yield Yₙ of
neutrons generated by muons in iron [6].

The detector data was used to determine the ratio of muons (µ⁺/µ⁻) stopped in the
substance, which characterizes the charge composition of the muon flux at the LVD depth. The ratio µ⁺/µ⁻ = 1.26 ± 0.11 (syst.) ± 0.04 (stat.) was obtained for the muon flux of a
near-vertical direction ( < 40 degree) at sea level in the range of 1 - 3 TeV with an average
energy of ∼1.8 TeV [7].

Using horizontal muons passing through the LVD and OPERA [8] setups located at a distance
of ~160 m, the time of flight of muons between the detectors was measured. The total live time
of the data in coincidence between the two experiments corresponded to 1200 days from mid
2007 until March 2012. We saw that in 2009 this time increased by (73±9) ns [9]. This helped
to find an error in the measurement of the neutrino velocity at the OPERA detector.

The time dependence of the muon flux Iµ(t) was obtained from the LVD data for 24 years
of operation of the setup. The obtained average muon flux is I₀µ = 3.35 ± 0.0005 (stat.) ± 0.03
(syst.) × 10⁻⁴ m⁻² s⁻¹ [10].

Describing the dependence Iµ(t) by the harmonic function Iµ(t) = I₀µ+δIµ×cos[2π(t−t₀)/Tm]
phase t₀ = (185 ± 15) days, which corresponds to the maximum muon intensity at the beginning
of July. The intensity modulations have an absolute amplitude δIµ = (5.0 ± 0.2) × 10⁻⁶ m⁻²
s$^{-1}$, its relative value $\delta I_\mu/I_\mu = 1.5\%$. We have observed that the flux of underground muons is modulated due to the temperature variations in the stratosphere whose main periodicity is seasonal. We have quantified a correlation by using the upper-air temperature data set obtained from the European Center for Medium-range Weather Forecasts, finding an effective temperature coefficient, $\alpha_T = 0.94 \pm 0.01$ (stat.) $\pm 0.01$ (sys.). This measurement is in good agreement with model predictions of muon production from $\pi, K$-decay as well as with other measurements at the same depth.

It was shown in [10] that the temperature of the atmosphere and, consequently, the intensity of muons, in addition to seasonal modulations, undergo irregular changes during the year. The data with the maximums and minimums of intensity for each year of observations are given in tabular form.

In addition, in the LVD experiment [11], the amplitude of seasonal variations of neutrons $\delta \Phi_n/\Phi_n$, produced by the muon flux, was determined. Unexpectedly, the $\delta \Phi_n/\Phi_n$ value turned out to be $\sim 6$ times higher than the amplitude of the variation of the muon intensity $\delta I_\mu/I_\mu$. The observed effect can be explained by variations in the average muon energy $\delta E_\mu/E_\mu$ [12]. From the data of the LVD experiment, it follows that the amplitude of variations $\delta E_\mu/E_\mu$ at the depth of the LVD should be $\sim 10\%$ in order to provide, together with variations in the intensity of muons $\delta I_\mu/I_\mu = 1.5\%$, the amplitude of variations in the flux of cosmogenic neutrons 9.3%, measured at LVD [11].

In the latest LVD experimental results, the values of variation for near-horizontal and near-vertical muons were obtained [13]. This investigations refer to high-energy muons: the threshold energy (a 50% survival probability) for muons at sea level is $E_{th}^{\mu} \approx 1.8$ TeV for vertical muons and $E_{th}^{\mu} \approx 4.7$ TeV for near-horizontal muons.

4. Conclusion
The Large Volume Detector is triggered by atmospheric muons. The data collected over almost a quarter of century are used to study the muon intensity underground. The monitoring of the muon background is a relevant information for an underground laboratory, especially for rare events searching for.

Acknowledgments
The work was carried out with partial support from the grant of the the Russian Foundation for Basic Research 18-02-00064.

References
[1] Agafonova N Yu et al. (LVD Collaboration) 2015 Astrophys. J. 802 47
[2] Bari G et al. 1988 Nucl. Instrum. Methods. Phys. Res. A 264 5
[3] Aglietta M et al. (LVD Collaboration) 1992 Nuovo Cim. A 105(12) 1793
[4] Agafonova N Yu et al. (LVD Collaboration) 2011 Bull. Russ. Acad. Sci.: Phys. 75(3) 408
[5] Aglietta M et al. (LVD Collaboration) 1998 Phys. Rev. D 58 092005
[6] Agafonova N Yu et al. (LVD Collaboration) 2015 Bull. Russ. Acad. Sci.: Phys. 79(3) 401
[7] Agafonova N Yu et al. (LVD Collaboration) 2013 Measurement of muon charge ratio with the Large Volume Detector Preprint 1311.6995
[8] Acquafredda R et al. (OPERA Collaboration) 2009 J. Instrum. 4 04018
[9] Agafonova N Yu et al. (LVD and OPERA Collaborations) 2012 Eur. Phys. J. Plus 127 71
[10] Agafonova N et al. (LVD Collaboration) 2019 Phys. Rev. D 100 062002
[11] Agafonova N Yu 2017 Measurement of the muon-induced neutron seasonal modulation with LVD Preprint 1701.04620
[12] Malgin A S 2015 J. Exp. Theor. Phys. 121(2) 212
[13] Agafonova N et al. Phys. At. Nucl. 2020 83(1) 69