Seasonal variations of the near-horizontal muon flux measured with the LVD underground detector

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The main goal of LVD is searching for neutrino radiation from stellar core collapse.
Muon events in LVD

Depth-intensity curve

Maximum depth for μ

Large θ angles toward the northeast correspond to depths of about 5 km w.e.

Modular structure

The LVD consists of three towers. It has 7 levels and 5 columns in each tower.

The scheme of the setup

CERN

Northeast

Long axis

38.4°
For high-energy muons (~280 GeV), which we are detecting underground, there is a positive temperature effect. Muons that reach great depths are produced, generally, in the decays of pions of the first generation. The number of these decays increases with the expansion of the atmosphere and the fall of its density in the upper layers (at an altitude of ~30 km).

\[ \alpha_T = 0.93 \pm 0.02 \]

The correlation of the change in the muons' intensity and the change in temperature is described by:

\[ \frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}^0} \]
2.5 million muon events for 2724 days during 2001-2008 were analyzed.

\[ I_\mu = I_0^\mu + \delta I^\mu \cos \left( \frac{2\pi}{T} (t - t_0) \right) \]

Average intensity
\[ I_0^\mu = (3.31 \pm 0.03) \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1} \]

Modulation value
\[ \delta I = (1.5 \pm 0.1)\% \]

Modulation period
\[ T = 367 \pm 15 \text{ дней} \]

Modulation phase
\[ t_0 = 185 \pm 15 \text{ дней} \]
Near Vertical Muons

\[ <E_\mu> \approx 270 \text{ GeV} \]
\[ <H> \approx 3.3 \text{ km w.e.} \]
\[ <\theta> \approx 13^\circ \]

Near horizontal muons

\[ <E_\mu> \approx 340 \text{ GeV} \]
\[ <H> \approx 5 \text{ km w.e.} \]
\[ <\theta> \approx 75^\circ \]

For horizontal \( \pi \) producing \( \mu \), the decay thickness in the upper atmosphere is much greater than for pions in vertical direction.
Event selection:
Muon hits at least 2 counters in detector.

An example of the passage of a muon in construction of 6 counters:
№1 – muon will not detect
№2 – muon will detect
№3 – muon will not detect

Muon hodoscope of two counters = equal acceptance method

In each month, pairs of counters were selected, so that the difference in the counting rate of the counter from the average was no more $|R_i - \langle R \rangle| = 10\%$.

Distribution of counting rates of muon pulse counters with energy $E > 50$ MeV
The muon hodoscope of the horizontal direction forms the counters of the same level, standing through one. We linked the counters in pairs. Such coupled pairs in the detector can be 672 max.
Muon hodoscope of two counters

vertical direction $\theta: 0^\circ - 30^\circ$
The seasonal variations of horizontal muons

\[ \langle H \rangle = 4980 \pm 250 \text{ m w.e.} \]

\[ \langle \theta \rangle = 76 \pm 2 \]

\[ N_{\text{hor}} = 2.6\% N_{\text{tot}} \]

\[ E_{\text{tr}} > 50 \text{ MeV} \]

\[ N_{\text{sc}} > 2 \]

Epoch folding method

\[ f(t) = I^h_{\mu} + \delta I^h_{\mu} \times \cos(2\pi(t-\varphi)/365) \]

\[ N_{\text{hor}} = 0.66 \text{ d}^{-1} \text{ pair}^{-1} \]

\[ t_{\text{max}} = 182 \text{ d} \]

\[ \delta = \frac{0.011}{0.66} = 0.017 \]
Near-vertical muons

Epoch folding method

\[ \delta I_\mu = 1.0\% \]

Residual method

summer: 3731 ev./c.
winter: 3647 ev./c.
\[ \delta I_\mu = 1.1 \pm 0.06\text{stat} \pm 0.2\text{sys} \% \]

Near-horizontal muons

\[ \delta I_\mu = 1.7\% \]

summer: 763 ev./c.
winter: 736 ev./c.
\[ \delta I_\mu = 1.8 \pm 0.2\text{stat} \pm 0.2\text{sys} \% \]
In the case of elastic scattering on the nuclei of the substance of the detector, WIMPs can give recoil nuclei with energies from 1 to 100 KeV. The rate of WIMP detection should be modulated due to seasonal variations in the speed of the Earth relative to the center of the Galaxy and the galactic WIMP- “gas”. Due to the rotation of the Earth around the Sun and the movement of the Solar System in the Galaxy, the registration rate in summer exceeds the winter rate.

The counting rate of neutron producing by $\mu$ has seasonal variation, like WIMP!

DAMA/LIBRA, XENON100, XMASS Direct detection of cold dark matter - hypothetical particles of WIMPs

1. With the LVD data the characteristics of seasonal variations in the muon fluxes of different directions in the period from 2001 to 2018 were obtained. Using independent simple hodoscopes the amplitude and phase of seasonal variations for horizontal and vertical muons were determined.

   Modulation amplitude for horizontal muons is $\delta l_{\mu}^{\text{hor}} = 1.7 \pm 0.3 \%$
   Modulation amplitude for vertical muons is $\delta l_{\mu}^{\text{ver}} = 1.0 \pm 0.2 \%$.

2. This studies refer to high-energy muons: the threshold energy (50% probability of survival) of muons at sea level for vertical muons is $E_{\text{th}}^{\text{ver}} = 1.8 \text{ TeV}$, for horizontal muons is $E_{\text{th}}^{\text{hor}} = 4.7 \text{ TeV}$.

3. In the future, it is planned to determine the temporal characteristics of the neutrons produced by muons in vertical direction and horizontal one.
Thanks!
### comparison table

<table>
<thead>
<tr>
<th></th>
<th>All muons</th>
<th>Near Vertical Muons</th>
<th>Near horizontal muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta I_\mu$</td>
<td>1.5%</td>
<td>1.1%</td>
<td>1.7%</td>
</tr>
<tr>
<td>$&lt;H&gt;$, km w.e.</td>
<td>3.72</td>
<td>3.57</td>
<td>4.98</td>
</tr>
<tr>
<td>$&lt;\theta&gt;$</td>
<td>28</td>
<td>13</td>
<td>75</td>
</tr>
<tr>
<td>$&lt;E&gt;$, ГэВ</td>
<td>280</td>
<td>260</td>
<td>340</td>
</tr>
<tr>
<td>$I_{\text{max}}$</td>
<td>185</td>
<td>182</td>
<td>178</td>
</tr>
<tr>
<td>$\delta N_n$</td>
<td>7.7%</td>
<td>6.4%</td>
<td>14%</td>
</tr>
</tbody>
</table>
Variations of muon intensity: features - not a sinusoid

$T = 365$

$195, 337, 560$

$142, 223$

$T = 365$
Вариации нейтронов, образованные горизонтальными мюонами