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Nuclear Instruments and Methods in Physics Research A 516 (2004) 96–103

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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CNGS beam monitor with the LVD detector

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Received 28 April 2003; received in revised form 19 July 2003; accepted 30 July 2003

Abstract

The importance of an adequate CNGS beam monitor at the Gran Sasso Laboratory has been stressed in many papers. Since the number of internal ν_μ CC and NC interactions in the various detectors will not allow to collect statistics rapidly, one should also be able to detect the ν_μ CC interactions in the upstream rock.

In this study, we have investigated the performances of the LVD detector as a monitor for the CNGS neutrino beam. Thanks to its wide area (13×11 m^2 orthogonal to the beam direction) LVD can detect about 120 muons per day originated by ν_μ CC interactions in the rock.

The LVD total mass is ~ 2 kt. This allows to get 30 more CNGS events per day as internal (NC + CC) ν_μ interactions, for a total of ~ 150 events/day. A 3% statistical error can be reached in 7 days. Taking into account the time characteristics of the CNGS beam, the cosmic muon background can be reduced to a negligible level, of the order of 1.5 events/day.

PACS: 14.60.Pq; 29.40.Mc; 95.55.Vj; 96.40.Tv

Keywords: CNGS beam; Liquid scintillator; LNGS; Neutrino oscillations; LVD; Muon transport in rock

1. Introduction

The CNGS beam from CERN to the Gran Sasso Laboratory (LNGS) is a wide-band high-energy ν_μ beam ($<E> \sim 23$ GeV) optimized for τ appearance. It provides ~ 2600 CC/kt/y and ~ 800 NC/kt/y at Gran Sasso [1], that is, assuming 200 days of beam-time per year, a total number of ~ 17 (CC + NC)/kt/day.

In order to provide an adequate monitoring of the beam performance it has been estimated [2]

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doi:10.1016/j.nima.2003.07.068

Table 1
Number of days needed to get 3% statistical error as a function of the number of CNGS events detected per day

CNGS events detected per day	No. of days needed to get 3% statistical error
50	22
100	11
200	5.5
500	2.2
1000	1.1

that one should be able to collect an event sample affected by a statistical error of the order of 3% in a few days time. In Table 1 the number of days needed in order to get this statistical significance is shown as a function of the total number of CNGS events collected per day at Gran Sasso.

Even considering an overall mass of the various experiments which will be active in GS at the beam start up as large as 5 kt, the number of CC and NC interaction per day, internal to the detectors, will be only ~ 80 and therefore more than 14 days will be needed to collect a sample with the statistical significance mentioned above.

The number of events observed per day can be increased considering the muons produced by the ν_μ CC interactions in the upstream rock, emerging into the experimental halls and detected either by a simple wide area dedicated monitor or by the running experiments.

The LVD experiment is primarily dedicated to the search for neutrinos from gravitational stellar collapses and has been running since 1991. In this study, we have investigated the beam monitor capabilities of the existing LVD detector [3], whose beam orthogonal surface is $13 \times 11\ \mathrm{m}^2$, larger than the other foreseen CNGS experiments. A detailed Monte Carlo simulation to estimate both the muon flux inside LVD and the number of detectable CC and NC internal interactions has been developed.

2. Event generation

The charged current interactions of the CNGS beam neutrinos have been simulated using the Lipari generator [4] in which neutrino interactions are calculated with GRV94 parton distributions [5] with explicit inclusion of the contribution of quasi-elastic scattering and of single pion production to the neutrino cross-sections. The neutrino energy has been sampled from the reference CNGS beam spectrum [1]. In Fig. 1 is shown the energy spectrum of ν_μ CC interactions, cross-section weighed. The muon energy at the interaction vertex is shown in Fig. 2 (left).

2.1. Muons generated in the rock

The muons originated in the rock by the beam neutrinos (*CNGS* μ), which have an angle of 3.2° (upward) from the horizon, have been propagated through the rock with MUSIC [6], a three-dimensional code which takes into account multiple scattering, energy losses due to ionization, bremsstrahlung, pair production and nuclear interactions. The muon energy spectrum after emerging from the rock is shown in Fig. 2 (right), while the zenithal and azimuthal angle in the LVD reference system are shown in Fig. 3.

The CNGS neutrino interactions, considered for the present study, are generated in a rock cylinder

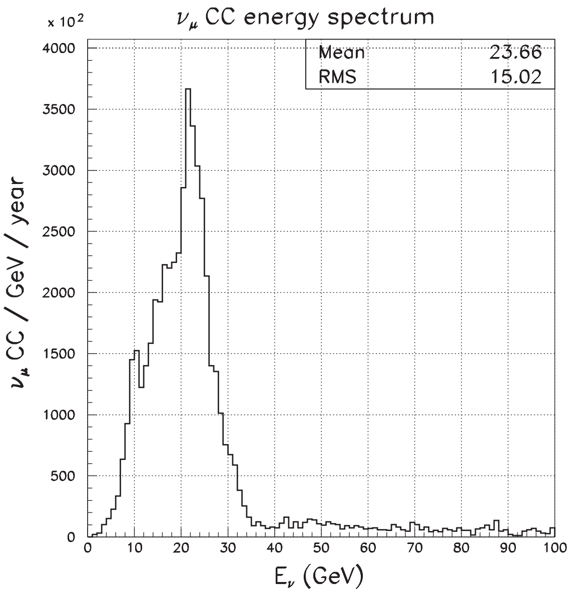

Fig. 1. Charged current ν_μ interactions energy spectrum of CNGS.

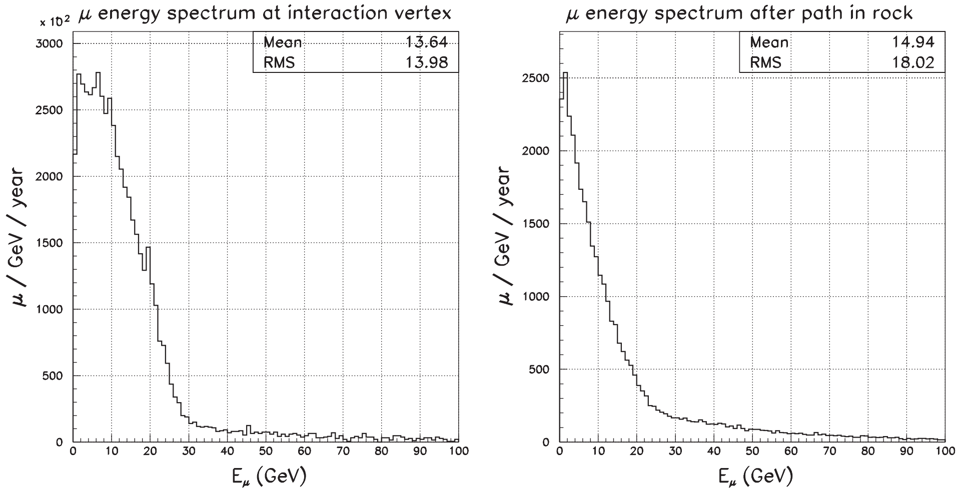

Fig. 2. Energy spectra of the μ generated in charged current ν_μ interactions at the interaction vertex (left) and after path in rock, when entering the experimental hall (right).

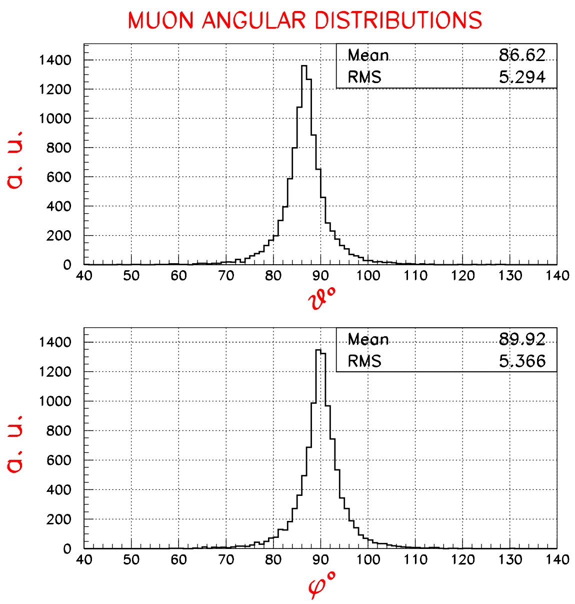

Fig. 3. Zenithal (top) and azimuthal (bottom) angle distributions of *CNGS* μ in the LVD reference system: $\theta = 90^{\circ} \equiv$ horizontal; $\phi = 90^{\circ} \equiv$ parallel to the Hall A-axis.

of height 370 m and radius 25 m, just in front of the LNGS Hall A. The cylinder and Hall A-axis coincide. The generation volume and mass are thus 726493 m^3 and 1969 kt. The muon range in the rock, in a first approximation, is given by

$$R = \frac{E_\mu}{\rho_{GS} \times dE/dX},$$

where the Gran Sasso rock density $\rho_{GS} = 2.71\ g/cm^3$ and $dE/dX = 2\ MeV/(g/cm^2)$. We assumed a maximum muon energy of 200 GeV that corresponds to a $\sim$370 m path in GS rock. This explains the choice of the cylinder height. We use a large radius (25 m with respect to the $13 \times 11\ m^2$ of LVD front surface) in order to take into account also muons originated far from the detector axis, but able to reach it because of their large angle (with respect to the beam direction).

The interaction vertex is selected uniformly in the cylinder volume. We define "Entrance LNGS (**EL**) Plane" the infinite vertical plane separating the rock cylinder face and the entrance wall of the experimental hall. The muon propagation from the interaction vertex to the LVD detector is subdivided into two main steps:

- The muons, generated with energy distribution according to Fig. 2 (left), are traced by MUSIC until they lose all their energy or until they reach the EL plane. The muons emerging from

Table 2
Number of muon detectable in LVD

Rock cylinder volume	$726,493\ m^3$
Rock cylinder mass	1969 kt
Nominal CNGS beam intensity	4.5×10^{19} pot/year
CC interaction probability	5.85×10^{-17} CC/pot/kt
ν_μ CC interactions in the rock	5.18×10^6/year
μ survival probability at the EL plane	6.8%
No. of μ at the EL plane	351,600/year
Probability to hit LVD "mother volume"	9.6%
No. of μ hitting LVD "mother volume"	33,600/year

Table 3
Number of internal CC and NC events in LVD

	Volume (m^3)	Mass (t)
Scintillator	1340	1044
Stainless steel	98.5	770
Total target		~1810 t
	CC	NC
ν_μ interactions in LVD	4770/year	1460/year
Total no. of internal events	6230/year	

the EL plane with non-zero energy are 6.8% of the generated events.

- The event is taken into account if the emerging muon direction points to a mother volume (13.75 m (horiz.) × 12 m (vert.) × 24.8 m (length)) which encloses the LVD detector and if the muon has enough energy to reach the LVD mother volume from the emerging point in the EL plane. This request is satisfied by 9.6% of the muons that emerge from the EL plane.

For comparison purposes we have calculated the total number of ν_μ CC interactions in one CNGS year (200 days) inside the rock volume using the number of CC/proton on target (pot)/kt and pot/year given in Ref. [1].

Accordingly, the number of muons hitting the LVD mother volume in 1 year is thus ~33,600, i.e. ~170/day.

A summary of the elements needed for the muon number calculation in LVD is shown in Table 2.

2.2. Internal CC and NC events

The LVD detector consists of 912 counters constituted of liquid scintillator in stainless steel tanks. Eight counters are grouped in a supporting structure (portatank) and 38 portatanks are arranged in a compact structure to form a LVD tower.

The total active scintillator mass is ~1050 t while the total mass of stainless steel tank and portatank, that can efficiently act as high energy neutrino target, is ~770 t. The interaction vertex of CC and NC internal events has been distributed uniformly in the apparatus. The number of events generated in steel and in scintillator is proportional to the relative weight of the two components.

The number of CC and NC events, at nominal beam intensity, are, respectively, 4770 and 1460/year, as shown in Table 3. The number of CC interactions is calculated accordingly to Ref. [1] while the ratio between the number of CC and NC interactions is calculated accordingly to the event generator described in Section 2.

3. LVD response

The detailed detector geometry and the particle interactions with the detector material have been taken into account with a GEANT simulation of the LVD detector (see Ref. [7] for a detailed description of the simulation code).

3.1. Event selection: muons generated in the rock

According to the simulation described in Section 2, 87% of the generated muon tracks hit the mother volume in the front face, while the remaining 13% enter LVD in the lateral faces (left, right, top, bottom).

Fig. 4 shows the distribution of the number of counters hit by the muons emerging from the rock. About 21% of them pass through the detector dead regions (corridors), and the corresponding

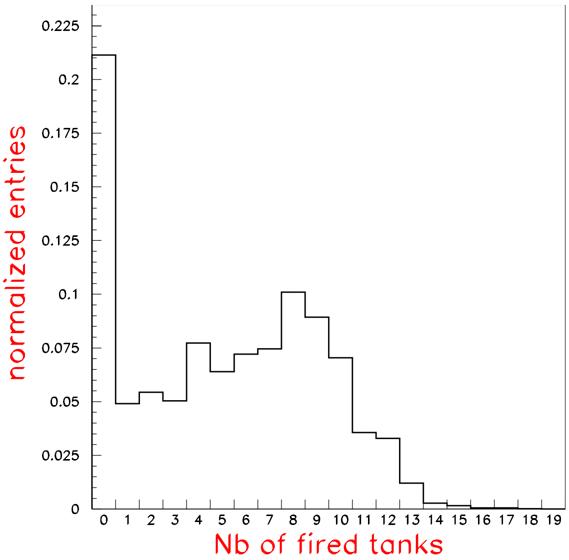

Fig. 4. Percentage of counters hit by *CNGS* μ per event.

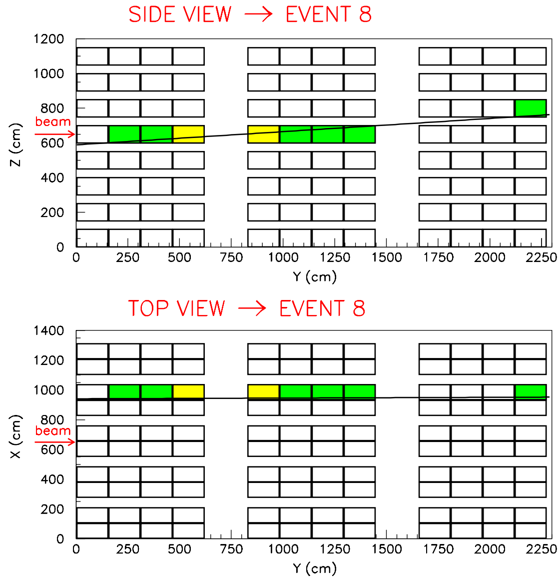

Fig. 5. Event display of a *CNGS* μ crossing eight scintillator counters.

geometrical efficiency is about 79%. See some event displays in Figs. 5 and 6.

Each scintillation counter is 1 m $\times$ 1 m of front area and 1.5 m along the beam direction. In Fig. 7 (top) the maximum energy released by muons in one single counter per event is shown. Fig. 7 (bottom) shows the number of counters with an energy release greater than 200 MeV, the entries being normalized to the total number of events with at least one fired counter. Assuming, as an event selection criteria, the presence of at least one counter with an energy loss greater than 200 MeV, we are able to detect 92% of the total number of muons entering an active part of the LVD detector (detection efficiency). The global efficiency (geometrical + detection) is thus 72%.

Therefore, the mean number of detected muons in LVD, at the nominal CNGS beam intensities, is about 24200/year, i.e. 120/day (see Table 4).

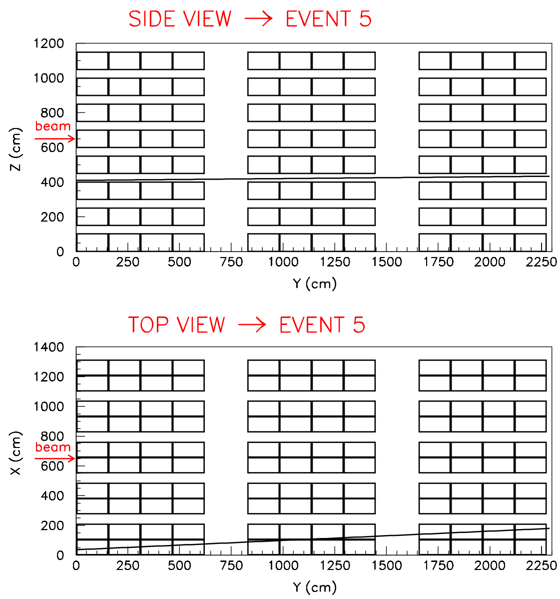

Fig. 6. Event display of a *CNGS* μ passing through a corridor.

3.2. Event selection: internal CC and NC events

In the case of neutrinos interacting inside the LVD detector, all the particles generated (muons and hadrons) are traced through the apparatus and the energy released in the scintillation counters is the sum of the contribution from all the traversing particles. Applying the same selection cut described in the previous paragraph (at least one counter with $E > 200$ MeV), the efficiency for

Table 4
Number of *CNGS muons* detected in LVD

No. of μ hitting LVD "mother volume"	33, 600/year
Geometrical efficiency	79%
No. of μ hitting LVD sensitive volume	26, 200/year
Selection cut efficiency	92%
No. of detected μ	24, 200/year

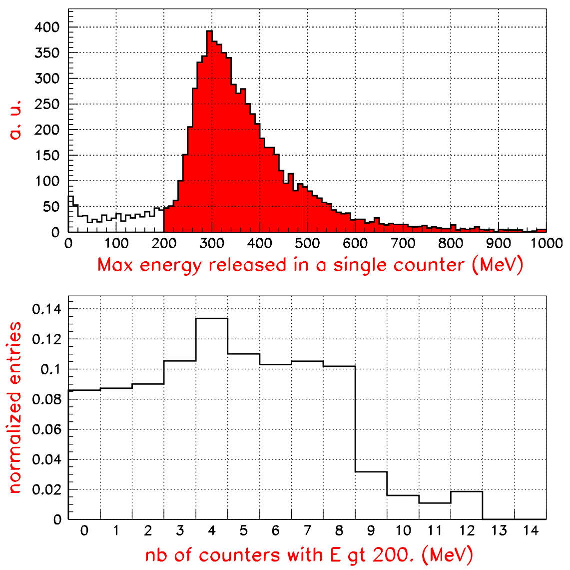

Fig. 7. Top: maximum energy loss in a single scintillation counter by a *CNGS* μ. Bottom: number of scintillation counters with an energy release greater than 200 MeV.

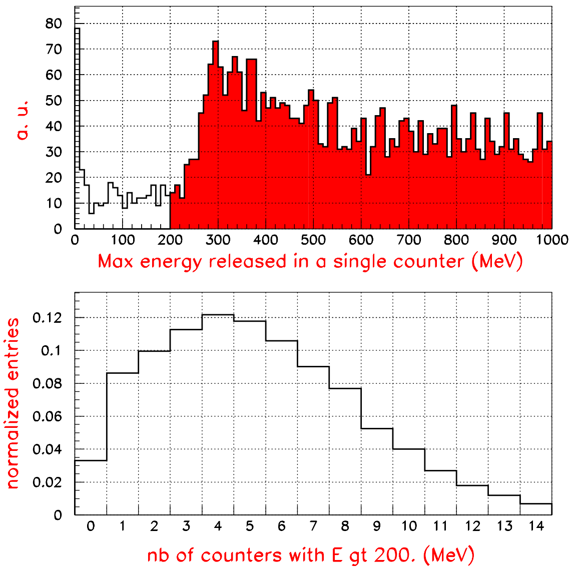

Fig. 8. Top: maximum energy loss in a single scintillation counter by internal ν_μ CC interactions. Bottom: number of counters with an energy release greater than 200 MeV.

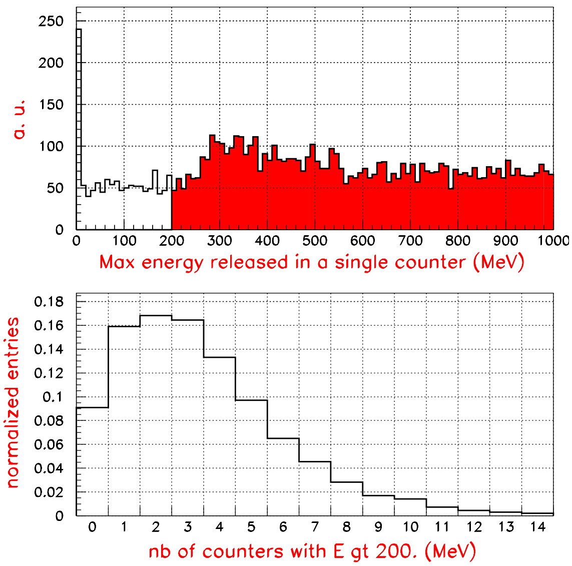

Fig. 9. Top: maximum energy loss in a single scintillation counter by internal ν_μ NC interactions. Bottom: number of counters with an energy release greater than 200 MeV.

the CC (NC) internal event sample is 97% (91%), as shown in Figs. 8 and 9. This gives $\sim$4630 CC and $\sim$1330 NC events in 1 year, corresponding to $\sim$30 additional CNGS events per day. Two examples of internal ν_μ CC and NC interaction event displays are shown in Figs. 10 and 11 (see Table 5).

4. Total event rate and background

We stress the point that here we are not interested in distinguishing between neutrino interacting in the rock events and internal neutrino events; the loose cut chosen has the advantage of a very good efficiency needed for a good monitoring task. Taking into account both the muons from CC interactions in the rock and the internal CC and NC interactions, the statistical error obtained during various number of days of run is shown in

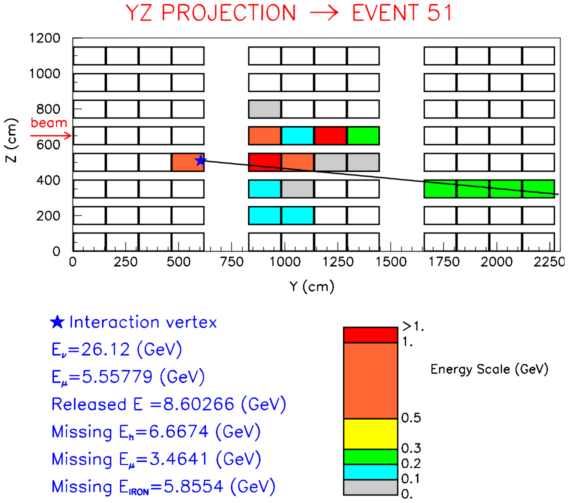

Fig. 10. Event display of CNGS ν_μ charged current internal interaction.

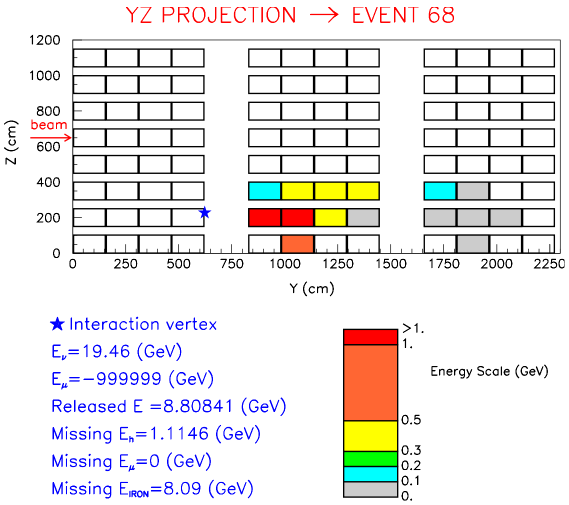

Fig. 11. Event display of CNGS ν_μ neutral current internal interaction.

Table 6. The main background source is due to cosmic muons. The rate in the whole LVD detector is about 9300 μ/day (about 6.5/min), considering the events with at least one scintillation counter fired by the muon. The requirement of at least one counter with an energy loss greater than 200 MeV rejects 20% of them, leaving about 7500 μ/day. Considering the 10^4 reduction factor due to the CNGS beam timing characteristics

Table 5
Number of internal CC and NC events detected in LVD

	CC	NC
ν_μ interactions in LVD	4770/year	1460/year
efficiency for the selection cut	97%	91%
No. of detected events	4630/year	1330/year
Total no. of detected events	5960/year	

Table 6
Statistical error on the number of CNGS events in LVD

Run duration (days)	Statistical error (%)
1	8.2
4	4.1
7	3.1
10	2.6

(10.5 μs of spill length and 50 ms inter-spill gap [8]), the actual number of background μ per day is ~1.5, practically negligible.

5. Comparison with a dedicated muon track detector

In order to evaluate the capabilities of a dedicated muon monitor at LNGS, we used the same software chain for the event generation and the muon propagation in rock. Thereafter, we simulate the event in the ideal detector.

We define the muon monitor as three vertical planes made of RPC's (or Limited Streamer Tubes) with 100% efficiency, separated by 1 m from each other along the beam direction. A muon is tagged when three planes are crossed by the muon track. At this level we do not add any consideration about the cosmic muon background rejection of this kind of detector, that must be studied in details. The number of muons detected per day by the detectors are shown in Table 7 for various transversal dimensions. We remark that the total number of CNGS interaction detected by LVD (muons from the rock + internal events) is similar to the number of muons seen by the biggest dedicated muon monitor.

Table 7
Number of muons detected per day by a dedicated muon track detector

Detector	Number of detected CNGS events
13 m × 13 m (as proposed in Ref. [2])	146 μ/day
13 m × 14.5 m (in the biggest Hall C)	165 μ/day
8 m × 9 m	63 μ/day
LVD	120 μ/day (+ about 30 internal events)

6. Summary and conclusions

The importance of a CNGS beam monitor apparatus in the experimental Halls of Gran Sasso Laboratory has been stressed in many papers [1,2]. In Ref. [2] it is pointed out that a geodesic misalignment of the whole beam system (proton beam, target, lenses, decay tunnel, muon chambers) can not be detected at the CERN site; it can be done only with a muon monitor at LNGS. Anyway, as it is shown in Ref. [2], due to the quite flat profile of the beam at LNGS, even a large geodesic misalignment (for example 0.5 mrad) produces only a 3% reduction in the ν_μ CC interaction rate (see Table 5 in Ref. [2]). This is the change in the rate that a LNGS monitor has to evaluate in a reasonable time.

In this paper the performances of the LVD detector as a monitor for the CNGS neutrino beam are shown.

Thanks to its wide area (13 × 11 m^2 orthogonal to the beam direction) LVD can detect about 120 μ/day using a very simple selection cut (at least one counter with an energy loss greater than 200 MeV). With a ∼2 kt total mass, LVD could detect 30 more CNGS events per day as internal (NC + CC) ν_μ interactions, for a total of ∼150 events/day. A 3% statistical error can thus be reached in 7 days (see Table 6). The cosmic muons background can be reduced to a negligible level, of the order of about one event per day, by taking into account the CNGS beam spill.

These results, as shown in Table 7, compare well with the expected performances of a dedicated muon detector.

Acknowledgements

This work is supported by the Italian Institute for Nuclear Physics (INFN) and in part by the Italian Ministry of Education, University and Scientific Research (MIUR) and the Russian Foundation of Basic Research (RFBR Grant 03-02-16413).

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