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CNGS beam monitor with the LVD detector.

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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 per 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 per day.

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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 $\sim$ 2600 $CC/kt/y$ and $\sim$ 800 $NC/kt/y$ at Gran Sasso [1], that is, assuming 200 days of beam-time per year, a total number of $\sim 17\ (CC + NC)/kt/day$.

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

CNGS events detected per day	Nb. of days needed to get 3% statistical error
50	22
100	11
200	5.5
500	2.2
1000	1.1

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

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 $\sim$ 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 $13 \times 11\ m^2$, larger than the other foreseen CNGS experiments. A detailed MonteCarlo 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 figure 2 (*left*).
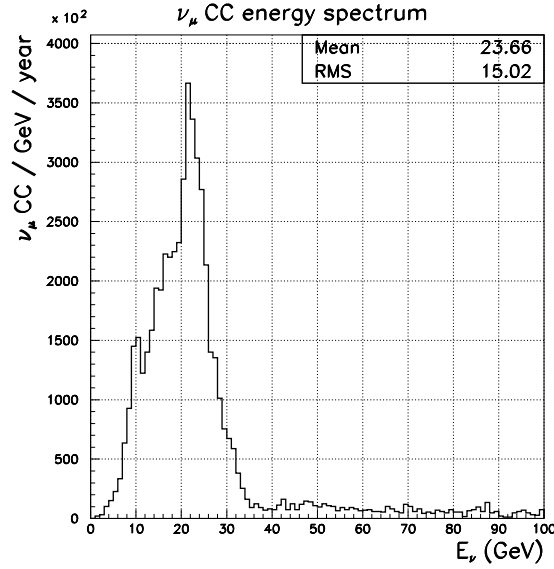

Figure 1. Charged current ν_μ interactions energy spectrum of CNGS.

2.1. Muons generated in the rock

The muons originated in the rock by the beam neutrinos (*CNGS muons*), 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 figure 2 (*right*), while the zenithal and azimuthal angle in the LVD reference system are shown in figure 3.

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

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

where the Gran Sasso rock density $\rho_{GS} = 2.71 \ g/cm^3$ and $\frac{dE}{dX} = 2 \ MeV/(g/cm^2)$. We assumed a maximum muon energy of 200 GeV that corresponds to a $\sim 370 \ m$ path in
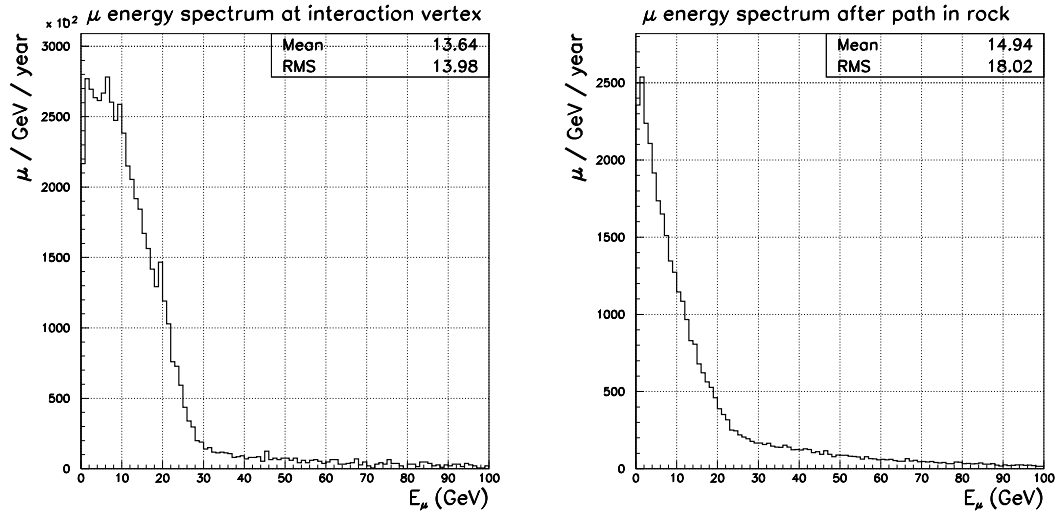
Figure 2. Energy spectra of the μ generated in charged current ν_μ interactions at the interaction vertex (*left*) and after path in rock, when entering the experimental hall (*right*).

GS rock. This explains the choice of the cylinder height. We use a large radius (25 m with respect to the 13×11 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 figure 2 (*left*), are traced by MUSIC until they lose all their energy or until they reach the EL plane. The muons emerging from 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 ($horiz.$) $\times 12$ m ($vert.$) $\times$ 24.8 m ($lenght$)) 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 one year is thus ~ 33600, i.e. ~ 170 per day.
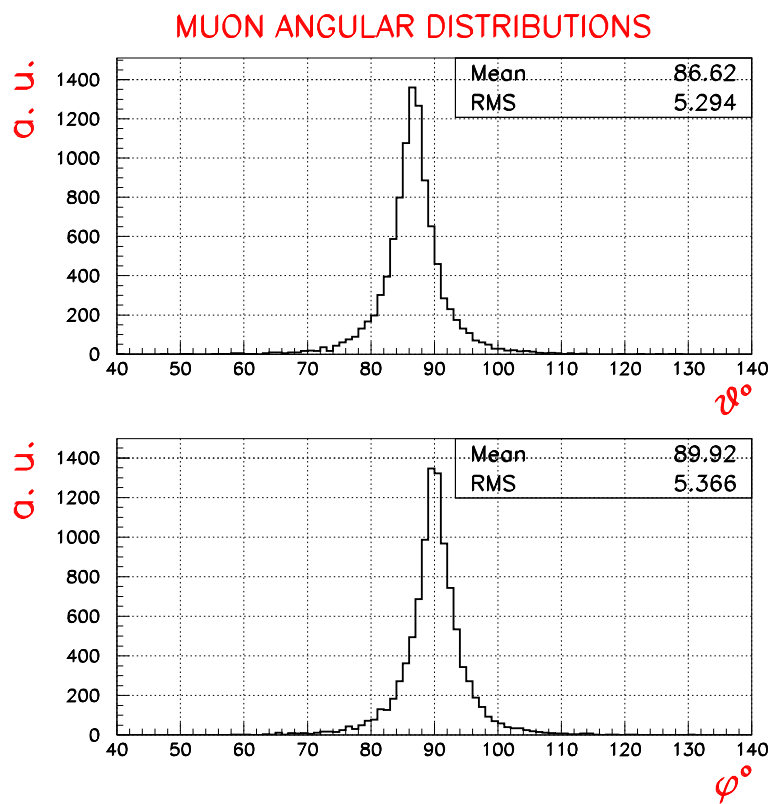
Figure 3. Zenithal (*top*) and azimuthal (*bottom*) angle distributions of *CNGS muons* in the LVD reference system: $\theta = 90^o \equiv$ horizontal; $\phi = 90^o \equiv$ parallel to the hall A axis.

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

Rock cylinder Volume	$726493\ m^3$
Rock cylinder Mass	$1969\ kt$
Nominal CNGS beam intensity	$4.5 \times 10^{19} pot/year$
CC Interaction Probability	$5.85 \times 10^{-17}\ CC/pot/kt$
ν_μ CC interactions in the rock	$5.18 \times 10^6\ per\ year$
μ survival probability at the EL plane	6.8%
Nb. of μ at the EL plane	$351600\ per\ year$
Probability to hit LVD "mother volume"	9.6%
Nb. of μ hitting LVD "mother volume"	$33600\ per\ year$

Table 2
Number of muon detectable in LVD.

2.2. Internal CC and NC events

The LVD detector consists of 912 counters constituted of liquid scintillator in stainless steel tanks. 8 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 $\sim 1050\ t$ while the total mass of stainless steel tank and portatank, that can efficiently act as high energy neutrino target, is $\sim 770\ t$. 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 per 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 paragraph 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 [7] for a detailed description of the simulation code).

3.1. Event Selection: muons generated in the rock

According to the simulation described in paragraph 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).

Figure 4 shows the distribution of the number of counters hit by the muons emerging

	Volume	**Mass**
Scintillator	1340 m^3	1044 t
Stainless Steel	98.5 m^3	770 t
Total Target		$\sim 1810\ t$
	CC	**NC**
ν_μ interactions in LVD	4770 *per year*	1460 *per year*
Total nb. of internal events	6230 *per year*	

Table 3
Number of internal CC and NC events in LVD.

from the rock. About 21% of them pass through the detector dead regions (corridors), and the corresponding geometrical efficiency is about 79%. See some event displays in figure 5 and 6.

Each scintillation counter is $1\ m \times 1\ m$ of front area and $1.5\ m$ along the beam direction. In figure 7 (*top*) the maximum energy released by muons in one single counter per event is shown. Figure 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 per year, i.e. 120 per day.

Nb. of μ hitting LVD "mother volume"	33600 *per year*
Geometrical efficiency	79%
Nb. of μ hitting LVD sensitive volume	26200 *per year*
Selection cut efficiency	92%
Nb. of detected μ	24200 *per year*

Table 4
Number of *CNGS muons* detected in LVD.

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
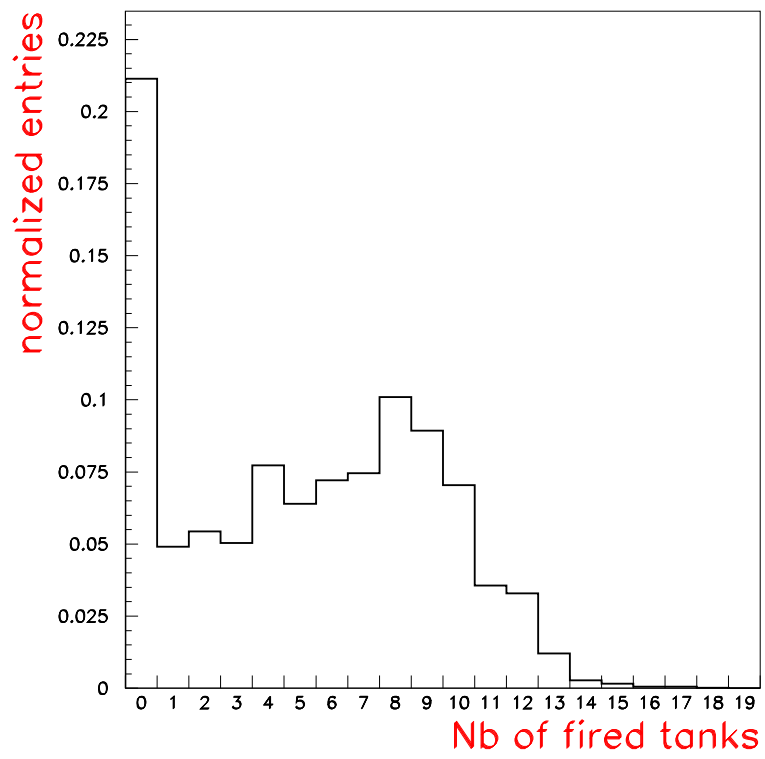
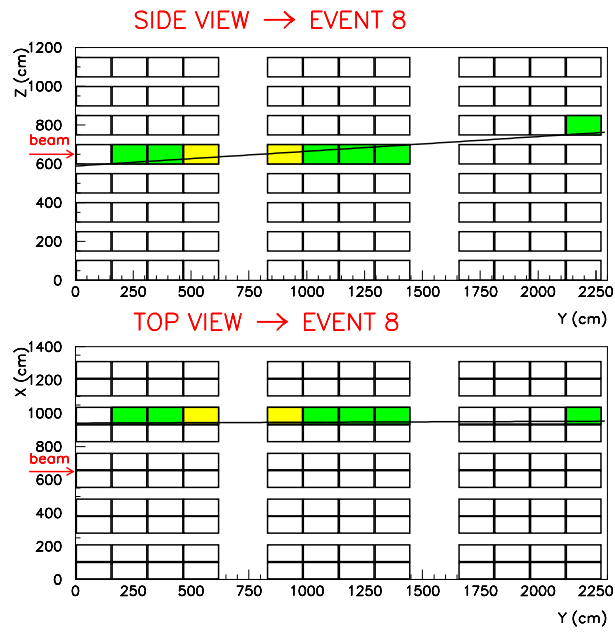Figure 4. Percentage of counters hit by *CNGS muons* per event.

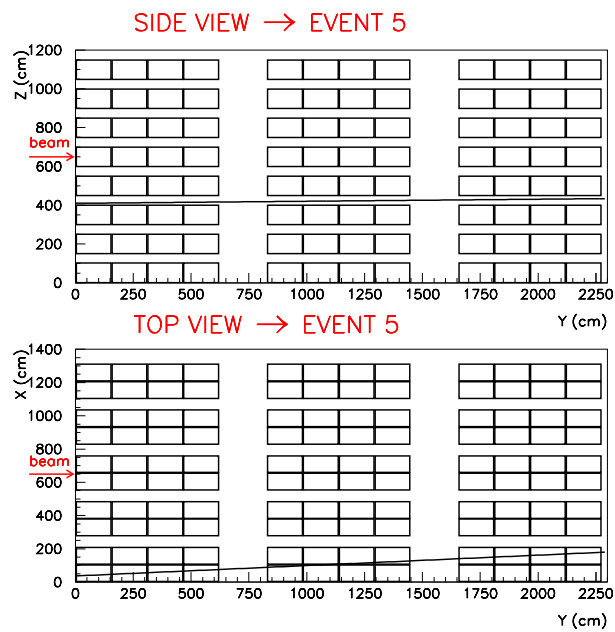Figure 5. Event display of a *CNGS* μ crossing 8 scintillator counters.

Figure 6. Event display of a *CNGS* μ passing through a corridor.
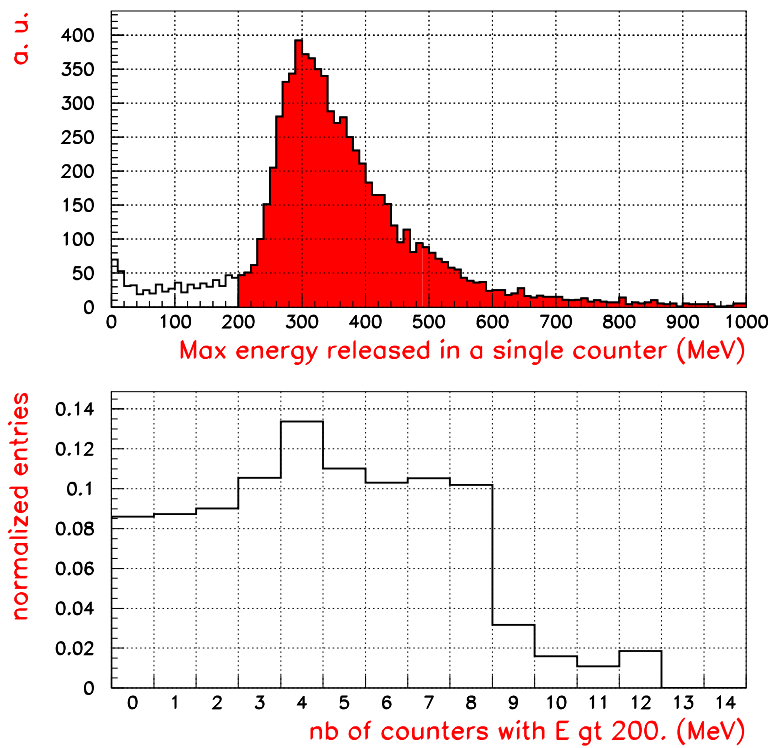
Figure 7. *Top:* Maximum energy loss in a single scintillation counter by a *CNGS μ*. *Bottom:* Number of scintillation counters with an energy release greater than 200 *MeV*.

with $E > 200\ MeV$), the efficiency for the CC (NC) internal event sample is 97% (91%), as shown in figures 8 and 9. This gives $\sim$ 4630 CC and $\sim$ 1330 NC events in one 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 figure 10 and 11.

	CC	NC
ν_μ interactions in LVD	4770 *per year*	1460 *per year*
efficiency for the selection cut	97%	91%
Nb. of detected events	4630 *per year*	1330 *per year*
Total nb. of detected events	5960 *per year*	

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

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 table 6.

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

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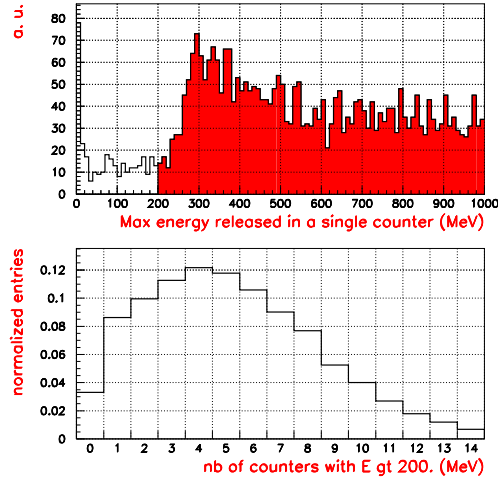Statistical error on the number of CNGS events in LVD.

Figure 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.
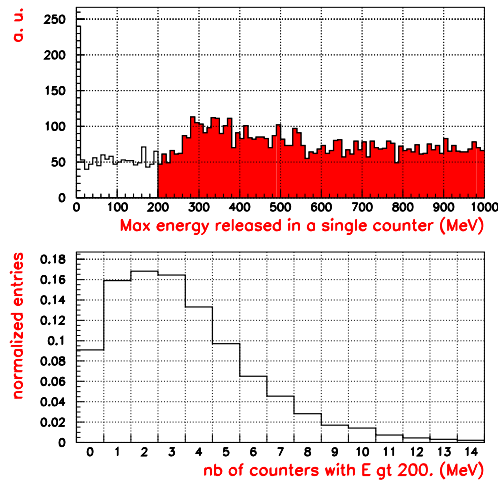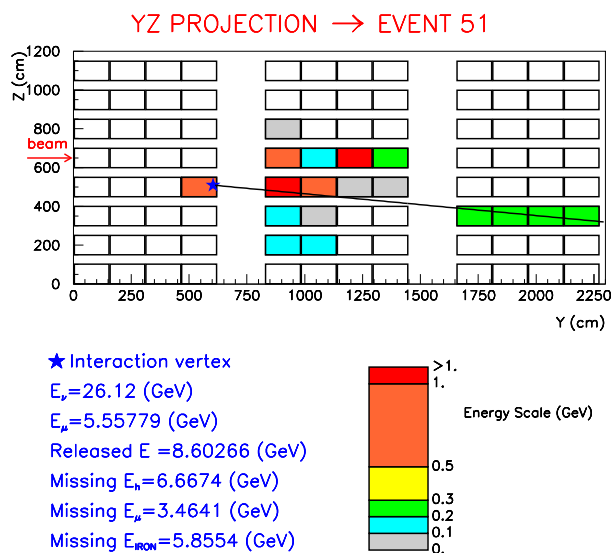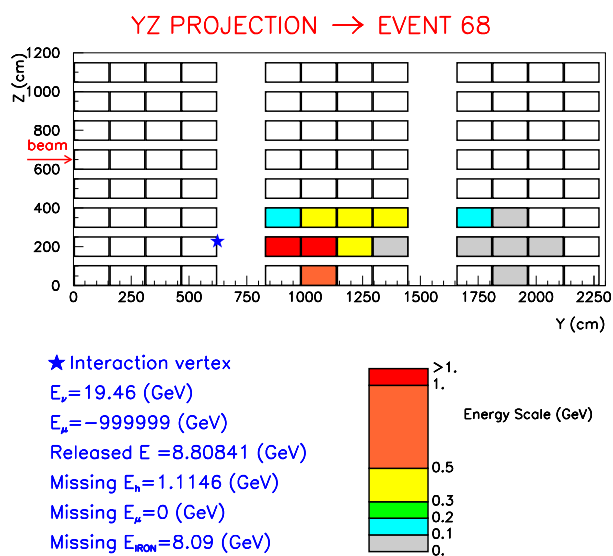

Figure 9. *Top:* Maximum energy loss in a single scintillation counter by internal ν_μ NC interactions. *Bottom:* Number of counters with an energy release greater than 200 MeV.

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

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

The main background source is due to cosmic muons. The rate in the whole LVD detector is about 9300 muons/day (about 6.5 per minute), 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 muons per day. Considering the 10^4 reduction factor due to the CNGS beam timing characteristics (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 don't 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 trasversal 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 muon seen by the biggest dedicated muon monitor.

Detector	Number of detected CNGS events
$13m \times 13m$ (as proposed in [2])	146 muons/day
$13m \times 14.5m$ (in the biggest hall C)	165 muons/day
$8m \times 9m$	63 muons/day
LVD	120 muons/day (+ about 30 internal events)

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

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 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 muons per 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 per 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 compare well with the expected performances of a dedicated muon detector.

7. Acknowledgements

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