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ScienceDirect
Nuclear Physics B (Proc. Suppl.) 188 (2009) 170–175
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
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Long baseline neutrino oscillations at Gran Sasso

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A short summary of the present long base line neutrino experiments in the Gran Sasso Laboratory using the CERN to Gran Sasso neutrino beam is given. This beam has been designed to provide unambiguous evidence for $\nu_\mu \to \nu_\tau$ oscillations.

1. MOTIVATIONS FOR THE CERN TO GRAN SASSO LONG BASE LINE NEUTRINO BEAM

Neutrino oscillations[1] were suggested by B. Pontecorvo in 1957 after the discovery of the $K^0 \leftrightarrow \overline{K^0}$ transitions and later by Maki, Nakagava and Sakata[2]. In 1968, the first experimental results from the Homestake detector showed a deficit in the solar neutrino flux: the value was at the level of 1/3 of the expected one[3]. This was the first hint of neutrino oscillation. After almost 40 years neutrino oscillations are now firmly established, thanks mainly to atmospheric neutrino and to solar neutrino experiments. Now the detailed study of oscillations with artificial neutrino beams has started. Neutrino oscillations have been studied in several experiments, now completed, inside the Gran Sasso Laboratory: we recall the GALLEX and GNO experiments searches for solar neutrino oscillations with Gallium, and MACRO, that searched neutrino oscillation using the atmospheric neutrinos.

The idea to have a CERN to Gran Sasso (CNGS) neutrino beam was present in the original design of the laboratory in 1979 and for this reason the orientation of the experimental halls was chosen pointing to the CERN site. However this idea was frozen for several years and only in 1995 a workshop was organized at the Gran Sasso laboratory dedicated to a possible neutrino beam. After the workshop there was a first call for letters of intent. Only in december 1999, after four years of discussions within the neutrino European groups, the beam was approved with a scientific program mainly dedicated to the ν_τ appearance, to be complementary to the already approved MINOS beam in the USA. This measurement is possible only with CNGS because MINOS and T2K have low energy beams unable to produce $\nu_\tau' s$. The CNGS construction started in the late 2000 and the first beam was delivered from CERN to the Gran Sasso experiments in August 2006, virtually on time with respect to the original schedule.

The CNGS neutrino beam was designed to provide unambiguous evidence for $\nu_\mu \to \nu_\tau$ oscillations in the region of atmospheric neutrinos, by looking for ν_τ appearance in a pure ν_μ beam. The energy $< E_\nu >= 17 GeV$ was chosen to optimize the number of ν_τ detected after a pathlength of 732 km. The main features of the beam are in Table 1.

2. THE GRAN SASSO LABORATORY AND THE CNGS BEAM

The Gran Sasso laboratory is the largest general purpose underground laboratory in the world for experiments in astroparticle physics and nuclear astrophysics (see Fig.1). It is used as a worldwide facility by scientists, at present: 756 in number, from 24 different countries, working

*The author wishes to thank many peoples of different experiments who have provided useful informations for this contribution and particularly M. Selvi (LVD), L. Perasso (BOREXINO), L. Scotto Lavino (OPERA), P. Sala (CNGS)

doi:10.1016/j.nuclphysbps.2009.02.039

$< E\nu_\mu >$	17 GeV
ν_τ prompt	negligible
$(\nu_e + \overline{\nu_e})/\nu_\mu$	0.87%
$\overline{\nu_\mu}/\nu_\mu$	2.1%
$< L/E >$	43 km/GeV
ν_μ CC/kton/year	2900
ν_τ CC/kton/year	16

Table 1
The CERN Gran Sasso beam (CNGS), rates assuming the design flux of 4.5×10^{19} protons on target/year and a running time of 200 days.

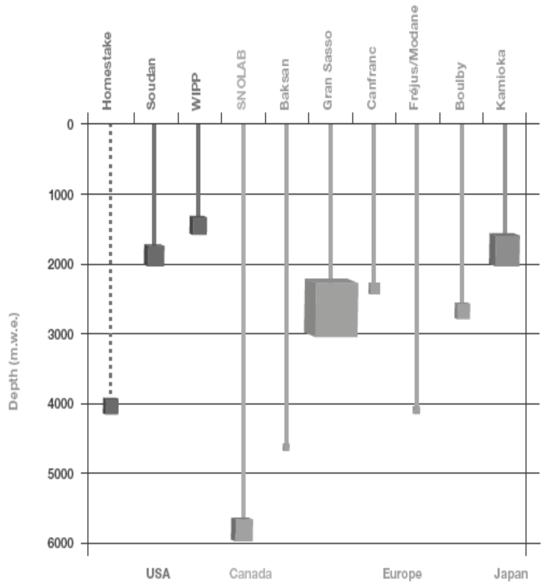

Figure 1. Depth (in meters of water equivalent) and space of the experimental halls of underground laboratories in the world. The Gran Sasso is the largest having in total 18000 m^2

on about 15 experiments in their various phases.

The coverage of the laboratory is 1400 m of rock corresponding to a cosmic ray muons reduction of the order of 10^{-6}. The coverage is not a crucial point for neutrino experiment with a beam but is very important for dark matter and double beta decay experiments. Now the laboratory is again completely operational, after a few years of reduced activity to improve safety after the accident in summer 2002 .

The laboratory has three experimental halls. The current allocation of the space in the experimental halls is shown in Figure 2.

The main research topics of the present programme are: neutrino physics with neutrinos naturally produced in the Sun (BOREXINO) and in Supernova explosions (LVD), neutrino oscillations with the beam from CERN (CNGS program, ICARUS and OPERA), search for neutrino mass in neutrinoless double beta decay (CUORE,GERDA), search for the violations of the Pauli principle (VIP), dark matter searches (DAMA,XENON,CRESST) and nuclear reactions of astrophysical interest (LUNA2).

The CNGS beam has been approved for the OPERA and ICARUS experiments. Particularly OPERA has been designed having in mind the high resolution tracking needed to identify on a single event basis the "kink" due to the τ decay. LVD and Borexino are also able to detect events produced by the neutrino interactions from the CNGS beam, but they are both on data taking and have been designed for other purposes. However they can be very useful for beam monitoring purposes.

The CNGS beam status is described with more details in another contribution to this conference[4]. As mentioned above, the CNGS facility was commissioned in 2006. Technical problems that prevented the operation in 2007 were successfully solved allowing a smooth operation and providing a total of 1.78×10^{19} proton on target in 2008. The CNGS beam started its operations on June 18th, 2008 and was stopped on November 3rd. The proton intensity reached 2×10^{13} protons per extraction, that is 83% of the nominal value.

3. OPERA AND ICARUS

The OPERA experiment, installed in hall C, is described in deeper detail in another contribution to this conference[5]. OPERA uses the CNGS

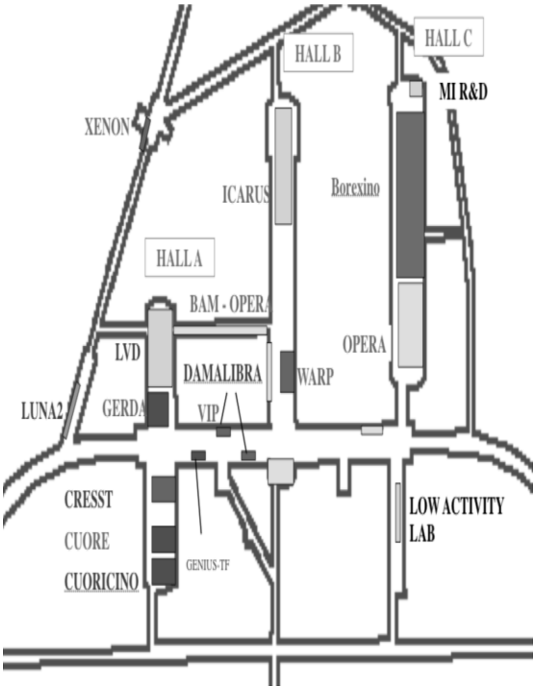

Figure 2. The three Gran Sasso Laboratory experimental halls and the space allocation. Some smaller experiments are located in the service tunnels

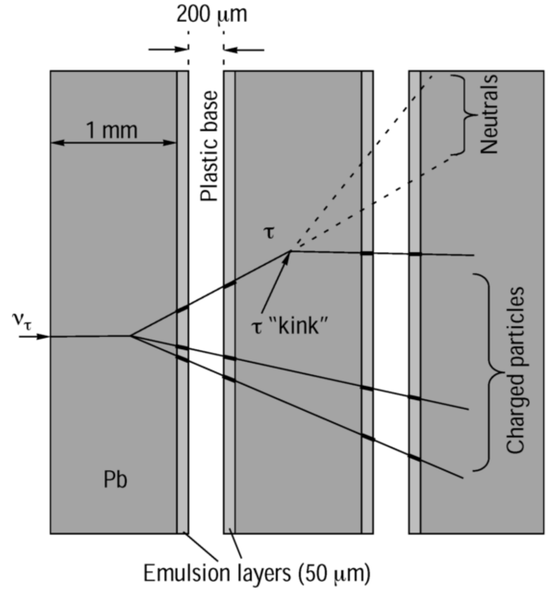

Figure 3. OPERA: the τ detection principle in the lead foils - nuclear emulsions sandwich (brick)

beam and a hybrid detector to perform direct observation of $\nu_\tau' s$ with a very low background. In order to detect $\nu_\tau' s$ OPERA will detect $\tau' s$ leptons produced during these interactions. An unambiguous signal of the presence of $\tau' s$ in the detector will be the precise detection of the τ decay topology. To this goal, OPERA uses lead foils as target and nuclear emulsions, assembled in units called bricks, for charged track detection. This technique is suitalbe to give track reconstruction accuracy (better than one micron) needed to detect the τ decay point (kink), while allowing for both coverage of large surfaces and high target mass. The detection principle is depicted in Figure 3. The neutrinos interact with the 1 mm thick lead target plates and the charged tracks are detected by the $50\mu m$ emulsion films, with a spatial resolution of about $0.5\mu m$. In addition to the emulsion detectors, OPERA has electronic detectors and a magnetic spectrometer. The main role of the electronic detectors is to select the emulsion to be scanned in order to identify the τ. In 5 years of data taking, OPERA should be able to observe 10 to 15 ν_τ events after oscillation at full mixing in the range $2.5 \times 10^{-3} \leq \Delta m^2 \leq 3.0 \times 10^{-3} eV^2$, with a total estimated background of 0.76 events.

The OPERA construction ended in July 2008 in time for the first long run with the neutrino beam. At the time of this conference OPERA observed 399 neutrino interactions in the bricks, in agreement with the predictions. At the end of the 2008 run, after the conference, OPERA detected 10058 on-time events and 1690 in the bricks[5].

The ICARUS Collaboration has developed, over a long lasting R&D programme, the Liquid Argon Time Projection Chamber (LAr TPC) technology, having as goal a several kton detector[6]. The current state of the art is represented

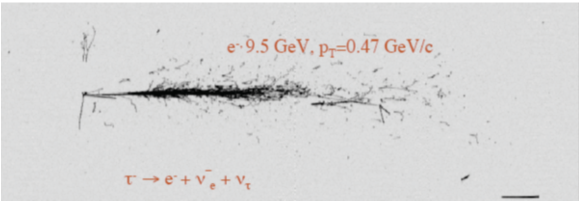

Figure 4. Simulated τ in ICARUS T600

by a 600ton detector (T600), which was built using fully industrial methods in about 5 years from 1997 to 2001. During 2001 the detector was activated and fully tested in a 3-month run, taking cosmic rays data in the assembly hall located in Pavia (Italy). The quality of the recorded data, subsequently analyzed during 2002-2003, demonstrates that the detector performances are consistent with those of laboratory-size prototypes. ICARUS is like an electronic bubble chamber with bubble size of the order of $3 \times 3 \times 0.4mm^3$.

After several delays mainly due to safety related problems, installation of the T600 detector in the hall B of Gran Sasso laboratory is now in a very advanced status. The filling with liquid argon should start at the beginning of 2009.

The physical program will be limited by the T600 mass. The main physics issues of the ICARUS experiment are the search for neutrino oscillations with direct observation of atmospheric and beam neutrinos and search for nucleon decay. Using kinematical cuts in 5 years of running ICARUS should be able to observe about $2\nu_\tau$ from CNGS (see Figure 4) with a background of about 0.1 events.

A strong R&D program with the ICARUS techniques is underway to realize neutrino near detectors with masses of the order of 100 Tons or giant detectors with masses of the order of 5-100 kton for the future generation of proton decay or neutrino oscillation experiment[7][8].

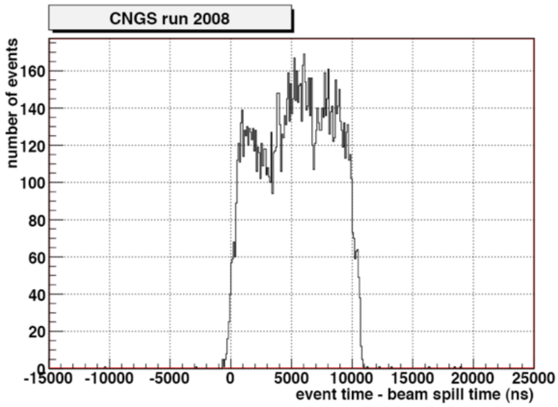

Figure 5. LVD arrival times of the CNGS neutrino events with respect to the starting time of the beam spill

4. LVD AND BOREXINO

The LVD detector, installed in the Hall A of CNGS has been designed for the search of neutrinos due to stellar collapse. However, as proven in [9][10], due to its large area and active mass, LVD can act as a very useful beam monitor, detecting the interaction of neutrinos inside the detector and the muons generated by neutrino interactions in the rock in front of the detector. The LVD active scintillator mass is about 1 kton, while the iron and stainless steel support structure is $\sim$ 0.9 kton It has a modular structure, made of 840 identical scintillation counters. Each counter is viewed on the top by three photomultiplier tubes. The front area of the whole detector (orthogonal to the CNGS beam) $\sim$ is $12 \times 10m^2$.

The CNGS events in LVD can be subdivided into two main categories: 1) CC charged current interactions in the rock in front of the detector: they produce a muon that can reach LVD and 2) CC and neutral current (NC) interactions in the material of LVD (liquid scintillator and iron). The muons from the rock represent about 78% of the total number of events, the internal CC interactions are 17% and the NC are 5%.

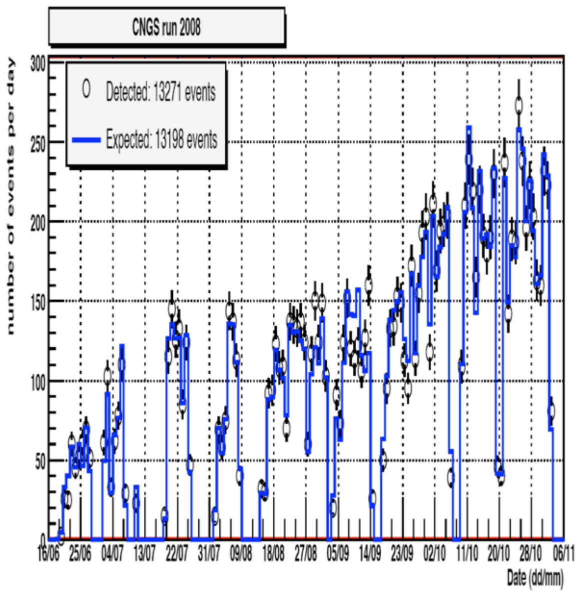

Figure 6. LVD CNGS neutrino events detected per day, compared with predictions.

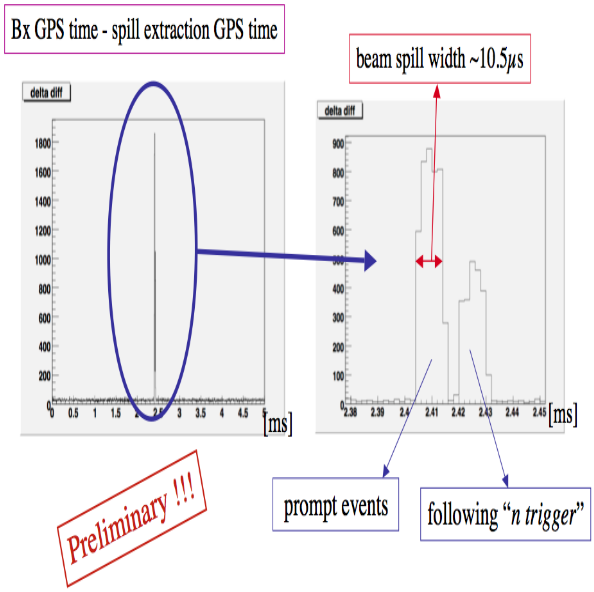

Figure 7. BOREXINO arrival times of the CNGS neutrino events with respect to the starting time of the beam spill; note the delayed events due to neutron capture.

During the whole 2008 run LVD was fully operative with 100% of uptime and with an average active mass of 970 t. The LVD events are filtered using a very loose selection cut, the requirement being: at least one scintillation counter with an energy release larger that 100 MeV. In this way 13271 events were detected in the time interval -15μsec $+25\mu$sec around the start time of the beam spill; their distribution in the time window is shown in figure 5. The detected events day by day and the expected rates are compared in figure 6 and are in very nice agreeement.

The BOREXINO solar neutrino low background detector, installed in hall C, is described with more details in another contribution to this conference[11]. To achieve ultra low operating backgrounds (both from internal and external sources) in the detector, the design of BOREXINO is based on the principle of graded shielding with scintillator at the center of a set of concentric shells of increasing radiopurity. The low background 0.3-kton scintillator sphere is contained in two spheres with non- scintillating pseudocumene. The entire detector is contained in a tank filled with water that is used for shielding but also as active Cherenkov detector for cosmic ray muons.

The CNGS neutrino events have energy much larger than solar neutrinos and therefore this water Cherenkov detector can be used to detect CNGS neutrino interactions. The event topology is similar to the one detected in LVD, with CC interactions in the rock before the detector and CC or NC internal interactions. It is important to note that BOREXINO is in the same experimental hall of OPERA and that there are several tens of common events per day in both OPERA and BOREXINO. The arrival times of the CNGS events of the 2008 run, up to the time of this conference, are shown in Figure 7; note the presence of secondary events due to neutron capture.

5. CONCLUSIONS

The 2008 CNGS neutrino run has been very successful. This is the first successful example of long base line beam produced by an accelerator complex in two countries (France and Switzerland) and detected in another country (Italy).

However, in order to collect the planned number of $\nu_\tau' s$ in OPERA in 5 years, it is important to achieve improvements in the beam intensity. Various possible improvements schemes are discussed in [12]; after several upgrades of the machine complex an ultimate factor 5 should be possible. In principle, this supports the idea discussed in[7] to have an off axis experiment using an ICARUS like detector dedicated to the θ_{13} measurement (MODULAR proposal). But unfortunately this idea was proposed too late to be competitive with the planned new generation of experiments expected to start next year.

REFERENCES

1. B. Pontecorvo J.Exptl. Theoret. Phys. 33, 549 (1957), Z. Maki, M. Nakagava and S. Sakata, Prog. Theor. Phys. 28, 870 (1962).
2. S. M. Bilenky, arXiv:hep-ph/0410090.
3. Davis R. et al.: Phys. Rev. Lett. 20,(1968) 1205.
4. D Autiero et al.: these procedings
5. L. Scotto Lavina : these procedings
6. C.Rubbia, CERN-EP/77-08(1977) and Icarus collaboration , a second generation proton decay experiment and neutrino observatory at the Gran Sasso Laboratory, LNGS-P28/2001
7. B. Baibussinov *et al.*, Astropart. Phys. 29, 174 (2008) [arXiv:0704.1422 [hep-ph]].
8. A. Badertscher *et al.*, arXiv:0804.2111 [hep-ph].
9. M. Aglietta *et al.*, Nucl. Instrum. Meth. A 516, 96 (2004) [arXiv:hep-ex/0304018].
10. N. Y. Agafonova *et al.*, Eur. Phys. J. C 52, 849 (2007) [arXiv:0710.1536 [hep-ex]].
11. L Ludhova : these proceedins
12. M. Meddahi and E. Shaposhnikova CERN report CERN-AB-2007-013