Plans for Neutrino Super Beams in Europe

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Abstract

Neutrino Super Beams use conventional techniques to increase the neutrino beam intensity compared to the present neutrino facilities. The first part of these facilities consists of an intense proton driver producing a beam higher than a MW power. The protons hit a target able to afford the high proton beam intensity. The produced charged particles are focused by a system of magnetic horns towards the experiment detectors. The main challenge of these projects is to produce elements able to resist to the high beam intensity for many years. New high power neutrino facilities could be build at CERN profiting from the LHC upgrades. For this reason, the initial design of these upgrades has to include the possibility to go to high power facilities.

1 Introduction

The next generation of neutrino oscillation facilities will mainly have to observe the $\nu_1 \to \nu_3$ oscillation, measure the related θ_{13} angle and observe CP violation in the leptonic sector. According to the amplitude of θ_{13}, the future facilities will accurately measure these parameters or just make discoveries.

First hints of large θ_{13} value have started appearing ([1–5]) giving $\sin^2 2\theta_{13} \sim 0.08$ with large uncertainty. If this value is of this order of magnitude, the new reactor experiments under preparation (Double Chooz, Daya Bay and RENO) and T2K will be in good position to discover this remaining oscillation during the next 2–3 years. In this case, the Super Beam projects will have the opportunity, not only to observe this phenomenon, but also observe for the first time CP violation in the leptonic sector and make precise measurements.

The starting point of a Super Beam is a proton driver providing the necessary power to produce intense neutrino beams allowing the execution of the physics program in a reasonable time (below 10 years) and in a cost effective way (below 1 billion euros including the detector cost). To keep the cost low, the European projects propose to use already existing installations or use installations which will be built for high priority projects as LHC upgrades.

Important decisions are expected in 2012–2013 concerning the next accelerator facilities when convincing results will be obtained by the LHC experiments and when the $\sin^2 2\theta_{13}$ limit will go down at the level of 10^{-2}.

2 The CERN acceleration upgrade program

Since few years, CERN has launched studies on replacement or upgrade of its machines composing its present acceleration complex [6]. The aim of these modifications is first of all to increase the reliability of the present system (the present CERN accelerators are very old) and prepare the upgrades needed by the SLHC. To increase the brightness of the beam in the LHC to allow for phase 2 of the LHC upgrade, an increase of the injection energy in the synchrotrons is needed.

Fig. 1 summarizes the CERN acceleration system under study. With injection at 160 MeV from the new Linac4 (under construction), the PSB will be able to deliver a beam with twice the brightness. To improve the situation in the SPS, the new PS2 (supposed to replace the PS) will provide a proton beam of 50 GeV. The size of a 50 GeV synchrotron and the requirements to reliably cope with the maximum brightness ever necessary for the SLHC, led to an injection energy of $\sim$ 4 GeV. For this

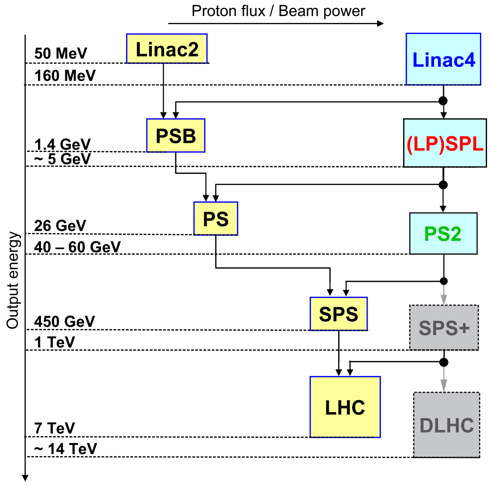

Fig. 1: Present (left) and possible new (right) CERN acceleration system.

injector, a superconducting proton linac (SPL [7]) has been chosen presenting significant advantages in the CERN context, especially because of its flexibility and its capability to evolve towards the very large beam power expected by, e.g., the future neutrino facilities [8]. This potential possibility is the decisive argument in favour of a linac–based PS2 injector with respect to an RCS–based solution.

3 High intensity neutrino beam using the CNGS

Before investigating about new facilities, an upgrade of the CNGS [9] has been studied in the framework of the MODULAr proposal [10]. This project proposes to use a 20 kton LAr TPC as a first step located at 10 km off–axis of the present LNGS underground laboratory and use a part of the existing CNGS installations. Two options are considered, one with a shallow detector just dedicated to the neutrino beam physics program and a second one in 1200 mwe depth in order to add to the physics program proton decay and cosmic neutrino searches.

For this project, a significantly higher intensity CNGS beam is needed compared to the present one. A study done by CERN [11] has shown that the maximum achievable intensity which could be reached after the upgrade of the whole CERN accelerator complex (future injectors, new SPS RF system, new CNGS equipment design) corresponds to 24.5×10^{19} p.o.t. for 200 days of operation with 80% SPS machine availability. In this study it is assumed that the present CNGS facility with small improvements can reach between 5×10^{19} p.o.t. (45% SPS availability) and 9.4×10^{19} p.o.t. (85% SPS availability).

For MODULAr project, the CNGS target and horns have to be redesigned. Fig. 2 presents the optimal neutrino spectrum calculated with new optics (SPS at 400 GeV). This spectrum is very similar to the one expected for NOVA project (NUMI at 120 GeV). Fig. 3 presents the MODULAr performance concerning $\sin^2 2\theta_{13}$ for a CNGS intensity of 1.2×10^{20} p.o.t./year (half of the theoretical CNGS maximum limit) and of 4.3×10^{20} p.o.t./year (nearly two times more than the theoretical CNGS maximum limit) compared with NOVA and T2K (phase 1). It has to be mentioned that the CNGS has been designed for a nominal value of 4.5×10^{19} p.o.t. never reached up to now. In 2008, the CNGS has delivered for OPERA experiment 1.8×10^{19} p.o.t. while it is expected for this year to deliver about 3.3×10^{19} p.o.t. (well below the assumed values of 5×10^{19} p.o.t. and 9.4×10^{19} p.o.t. mentioned above for the present CNGS performance). Thus, the missing intensity factor to reach the MODULAr requirements could be larger than the theoretical one.

In the CERN report [11], serious warnings are expressed concerning the possibility to replace CNGS elements (like the target and horn) after the present CNGS program has finished due to activation, not only of the target and horns, but also of the surrounding shielding. It has to be mentioned that, in

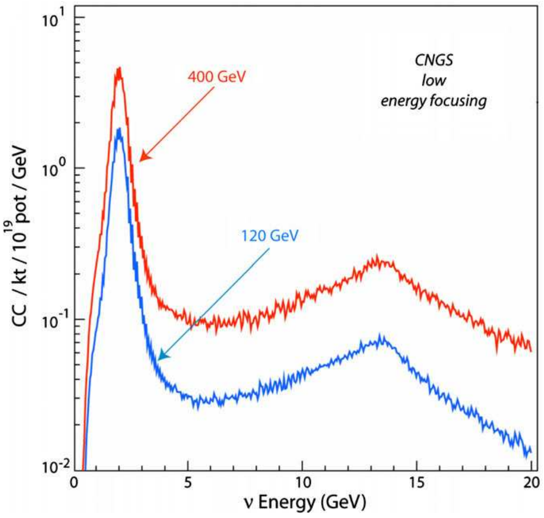

Fig. 2: Neutrino fluence for MODULAr (CNGS, 400 GeV) compared to the NOVA one (NUMI, 120 GeV).

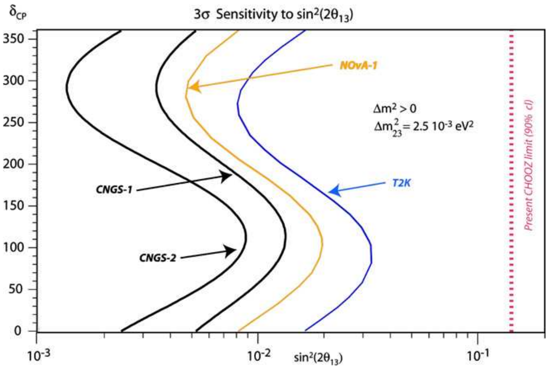

Fig. 3: MODULAr 3 σ sensitivity to $\sin^2 2\theta_{13}$ versus δ_{CP} for 1.2×10^{20} p.o.t./year (CNGS-1) and 4.3×10^{20} p.o.t./year (CNGS-2), compared to NOVA and T2K performance.

order to avoid these kind of problems and keep full upgradability, the T2K beam facility has anticipated and has built since the beginning the target station, the decay tunnel as well as the beam dump, in a way to be able to go up to 4 MW proton beam while the announced present goal is to go up to 1.66 MW.

4 High intensity neutrino beam using the PS2

Very recently, the utilization of PS2 to provide protons for a neutrino beam has been investigated in the framework of the European FP7 LAGUNA project [12, 13]. Fig. 4 presents the performance of such a project in the case where a 100 km LAr detector is placed in Pyhäsalmi mine in Finland ($0.25°$ off–axis, 2300 km from CERN, $2\nu + 8\bar{\nu}$ years).

For this study, a 50 GeV PS2 proton beam is considered with a beam power of 1.6 MW (360×10^{19} p.o.t./year). The result is promising but, according to CERN studies [14], the maximum PS2 achievable power, expected by the present design, is of the order of 0.32 MW, well below the power considered in the above studies. Moreover, for such utilization, the whole PS2 facility has to be built since the beginning taking into account the high power possibility.

5 High Power SPL

The possibility of constructing a High Power SPL to satisfy, not only the SLHC requirements, but also to provide protons to a neutrino facility, has been studied in [15] for a 2.2 GeV protons and [16] for an increased energy option of 3.5 GeV. Table 1 summarizes the main required characteristics of a High Power SPL (HP–SPL) for a Super Beam compared to the SLHC requirements (LP–SPL). The main difference between the two options, LP–SPL and HP–SPL, is the significant proton beam power and repetition frequency increase.

The necessary modifications to go from the low power to high power are given in [17]. Here, we insist on the possibility to foresee in the initial SPL design (to be decided around 2012) the high power option (especially concerning the radiation shielding around the facility) as it is already done for the Linac4 which is now under construction. This will avoid upgradability problems in the future as those mentioned before for the CNGS facility.

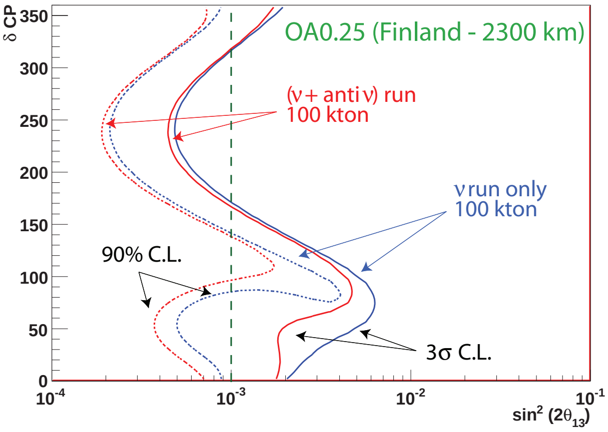

Fig. 4: Physics performance obtained using a high intensity PS2 proton beam and an off–axis detector placed in a distance of 2300 km and a 100 kton LAr detector.

Table 1: Low and High Power SPL characteristics for the SLHC (LP–SPL) and the Super Beam (HP–SPL) needs.

parameter	LP–SPL	HP–SPL
Kinetic Energy (GeV)	4	~ 4
Beam power (MW)	0.12	4 MW
Repetition frequency (Hz)	0.6	50
Protons/pulse ($\times 10^{14}$)	1.1	1
Av. pulse current (mA)	20	40
Pulse length (μs)	900	5

5.1 CERN to Fréjus Project (C2F)

The utilization of the SPL to produce a neutrino beam oriented towards the Fréjus tunnel has been investigated at the beginning of this decade [18] considered as the first stage of the Neutrino Factory complex.

Conventional muon neutrino beams are produced by the decay of mesons (pions and kaons). These mesons are produced by colliding a proton beam with a target. To send the neutrinos in the right direction, the only available possibility is to act on the direction of the charged mother particles. After the proton collision with the target, the emerging mesons are collected and focused towards the neutrino detector using a sign–selecting toroidal magnetic field. The hadron collector used very often in these applications is a magnetic horn pulsed with a very high electrical current.

In the case of the CERN SPL Super-Beam (SPL–SB) the operation conditions will be much more severe than in previous applications. Table 2 shows a comparison of some horns already used by past or ongoing projects. In this table one can see that the under investigation horn has a small length which could be an advantage during the fabrication and operation. But, on the other side, the proton driver power (4 MW) and repetition rate (50 Hz) are considerably higher than other applications inducing severe operation conditions.

An initial design of a horn prototype system (horn+reflector) foreseen for the Neutrino Factory has been made at CERN for a 2.2 GeV proton beam [19, 20]. An optimization and a redesign has been made in a Super Beam context [21, 22] driven by the physics case of a long baseline experiment (130 km) between CERN and Fréjus (MEMPHYS detector location [28]). From these studies, it came out that the optimal proton energy was between 3.5 and 4.5 GeV. Above these energies, the muon neutrino beam starts being contaminated by electron neutrinos mainly coming from kaon decays.

Both studies concluded that the proton target has to be installed inside the horn to maximize the

Table 2: Comparison of horns already used or under utilization with the SPL–SB proposed one.

Project	Proton Energy (GeV)	Power (MW)	Rep. Rate (Hz)	Current (kA)	Number of horns	Length (m)
CNGS	400	0.2	2 pulses/6 sec	150	2	6.5
K2K	12	0.0052	0.5	250	2	2.4–2.7
NUMI	120	0.4	0.5	200	2	3
MiniBoone	8	0.04	5	170	1	1.7
T2K	50	0.75	0.3	320	3	1.4–2.5
SPL-SB	3.5-5	4	50	300–600	2	1.5

hadron collection (Fig. 5). For the power dissipation of the system, this condition (imposed by the relatively low proton energy and the consequently low forward hadron boost) is a very sever constraint. Sever conditions will also be met by the target station and the target itself.

In the previous studies, a liquid mercury target 30 cm long has been considered as the one proposed for the Neutrino Factory. But, it has been shown (MERIT project [23]) that to maintain the liquid mercury jet integrity, the presence of a magnetic field higher than 10 T is necessary. This condition is only satisfied by the Neutrino Factory operation conditions where a solenoid is used as hadron collector, but not in the case of a magnetic horn where the magnetic field is confined inside the horn. Moreover, mercury is not compatible with aluminum alloys usually used in the horn manufacturing.

The main advantage of a liquid target is the power dissipation easily done by the liquid recirculation. A solid target utilization doesn't seem compatible with the very high power (4 MW) proton beam. Studies already done show that with the present knowledge, solid targets (e.g., graphite) can only afford proton beams up to 1.5 MW. Mainly for all these reasons, the target/horn integration has to be seriously studied since the beginning of the design.

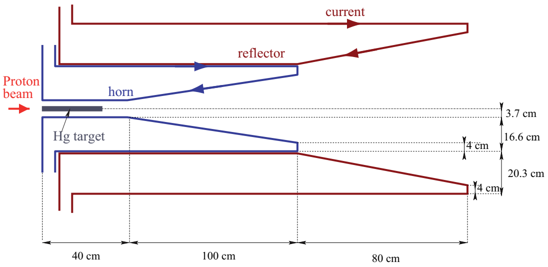

Fig. 5: Schematic view of the horn and reflector optimized for a 3.5 GeV SPL proton beam.

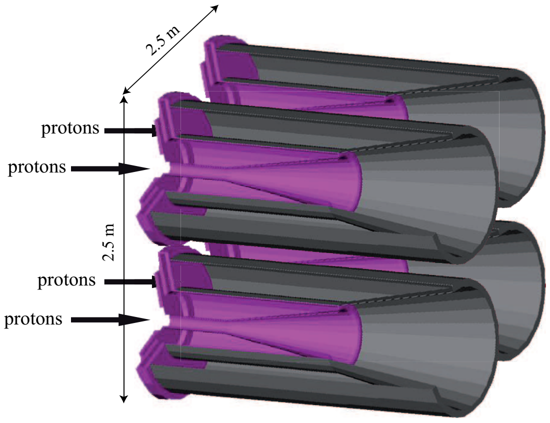

Fig. 6: Schematic view of 4 target/horn systems sharing the proton beam power.

5.2 Target/horn system

In the Super Beam baseline option of the project, the pions are produced by the impact of a primary 4 MW/3.5 GeV pulsed proton beam on a target located inside the horn (Fig. 5).

The magnetic horn under study will have to focus hadrons (mainly pions) with a mean momentum of 600 MeV/c parallel to the beam axis and towards a distant detector. The horn is composed of an aluminum as thin as possible skin (<3 mm) to minimize the energy deposition by the particles coming out of the target. To obtain the toroidal magnetic field needed for the hadron focusing, a high current circulates between the internal and external skins inducing inside the horn a magnetic field varying like $1/r$ where r is the distance from the horn axis. In this way, the magnetic field outside the horn completely vanishes in order the particles coming out to suitably stop spiring at the moment where their direction is parallel to the horn axis. The electrical current required to efficiently focus the hadrons is of the order of 300 kA for the horn and 600 kA for the reflector enveloping the horn.

The horn is submitted to a strong electromagnetic pulse producing thermo–mechanical stresses, vibrations, and fatigue reducing its lifetime. The current is brought from the pulse generator up to the horn using strip lines to avoid heating. These strip lines have to be well studied, especially their different connections to avoid breaking due to vibrations induced by the 50 Hz pulses. This project will benefit from the experience of the CERN prototype horn designed for 2.2 GeV proton beam, CNGS, Miniboone, and T2K horns.

The horn shape strongly depends on the hadron energy and thus on the primary proton beam energy. Since the first CERN design, the physics requirements have changed according to recent physics results leading to the actual required proton energy which is of the order of 4 GeV (matching the PS2 injection requirements) instead of 2.2 GeV. Mainly for this reason and to profit from new technological developments, a new horn design has to be done and a prototype has to be constracted again. An optimized horn design maximizing the neutrino beam intensity could improve the physics results.

Due to the very sever operation conditions, the whole system's integration including the target, the horn and the cooling system, has to be carefully studied. As mentioned before, with the present knowledge, it is impossible to use a solid target with a proton driver power higher than 1.5 MeV. In order to mitigate the high power beam effect, one could use 4 target/horn systems as depicted by Fig. 6 [25]. This takes advantage of the small horn size and from the reduced length of the hadron decay tunnel ($\sim$ 50 m) just after the horn which diameter can be increased to satisfy the 4 horn system. In this case, the proton beam power for each target/horn system is reduced to 1 MW. This scheme presents many advantages as less exposure to radiation and easier power dissipation. The main disadvantage comes from the beam sharing. To send the proton beam in the 4 systems, 4 proton lines will be needed (pulsed simultaneously or one after the other). These 4 beam lines will add an extra cost to the proton beam facility. To avoid this problem one could envisage a rotating 4 target/horn system as the one of Fig. 6 or a more linear translating system where the target/horn systems are on a straight line. In these last 2 cases, it is not any more needed to increase the diameter of the decay tunnel.

Concerning the target, other possibilities are under investigation as a fluidized jet of tungsten or tantalum particles in helium gas [26]. Flowing powder targets have the advantages of fluid targets without presenting the disadvantages of solid targets. The deposited power is easily dissipated due to the recirculation. They don't break because the shock waves are constrained within the material grains.

A tuning of the multiphysics simulations of the target/horn system (fatigue, deformations, modal analyses, transient thermo mechanical excitation of the structure, skin effect and Joule heating, power dissipation, heat exchange and cooling, radiation resistance, etc.) could be done using input provided by the previously mentioned facilities (mainly T2K phase 2 where a 1.66 MW proton beam will be used). To validate these simulations, some tests and R&D will be necessary (target irradiations, horn pulsing etc.) where CERN could play a leading role. These studies have also to include the design of a complete remote handling installation for the horn and target maintenance and possible exchange.

To reduce the length of the proton pulse from 0.57 ms (delivered by the SPL) to few μs (affordable by the current pulse duration sent to the horn), after the proton driver, a beam accumulator is normally needed but not a compressor as in the case of the Neutrino Factory [16].

The European FP7 Design Study EUROν [24] studies all aspects of feasibility of the target, horn and integration of the two objects.

5.3 Physics Performance

This facility gives promising results especially for relatively high θ_{13} values as those extracted by the combination of all experimental results [1–4] including very recently the latest SNO results [5]. In [21] is described the possibility to use a 3.5 GeV proton beam and a 440 kton Water Čerenkov detector located at Fréjus tunnel (130 km distance corresponding to the 1st oscillation maximum). Fig. 7 presents the neutrino and anti–neutrino expected spectra, while Fig. 8 gives the $\sin^2 2\theta_{13}$ sensitivity versus δ_{CP} compared to the T2HK one. One can see that this project could be sensitive to $\sin^2 2\theta_{13}$ for values lower than 10^{-3}.

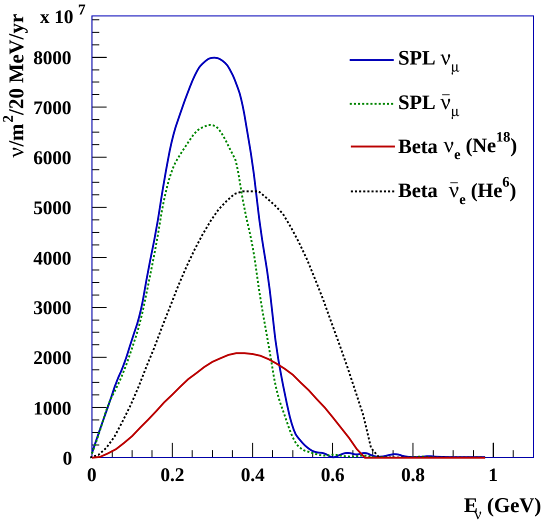

Fig. 7: Neutrino spectra for SPL Super Beam and CERN Beta Beam.

A very good synergy exists between this project and the CERN Beta Beam one ($\gamma \sim 100$) providing neutrinos of similar energy ($\sim$300 MeV) than those produced by the SPL Super Beam project (Fig. 7). The two projects could share the same detector placed at Fréjus tunnel. The combination of the results of both experiments (Fig. 8) increases considerably the physics performance of the whole project. This combination also allows to test separately CP, T, and CPT violation by two different ways using the oscillations $\nu_\mu \rightarrow \nu_e$, $\bar{\nu_\mu} \rightarrow \bar{\nu_e}$, $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu_e} \rightarrow \bar{\nu_\mu}$.

On top of that, the unoscillated neutrino beam of each facility would allow to measure the neutrino interaction cross–section of the other facility reducing significantly the systematic errors. The weak point of both facilities is the short baseline distance reducing considerably the possibility to observe matter effects and thus give information on mass hierarchy. Fig. 9 gives the sensitivity to this last parameter versus δ_{CP} (dotted lines). This sensitivity is significantly improved for all projects when combined with the accumulated atmospheric neutrino data (solid lines) in a way to be able to observe a 2σ effect for $\sin^2 2\theta_{13} > 0.02$.

Another possibility expressed recently improving much more the physics performance of this project is to send a Beta Beam to Fréjus detector ($\gamma \sim 500$, $d = 960$ km) from DESY using HERA to accelerate the radioactive ions [30].

The large Water Čerenkov detector MEMPHYS can also be used to study the proton lifetime and detect cosmological neutrinos (supernovae, solar, atmospheric) and geoneutrinos. All these possibilities are studied by LAGUNA. MEMPHYS can profit from the excavation of a safety gallery (under construction) to avoid any interference during installation and operation of the detector with the car traffic in the highway tunnel.

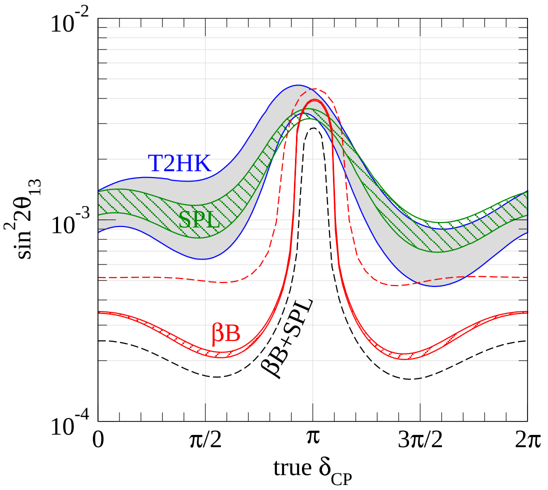

Fig. 8: 3 σ discovery sensitivity to $\sin^2 2\theta_{13}$ for SPL Super Beam, Beta Beam and T2HK as a function of the true value of δ_{CP} for $(5\nu + 5\bar{\nu})$ years running period for Beta Beam and $(2\nu + 8\bar{\nu})$ years for SPL Super Beam and T2HK.

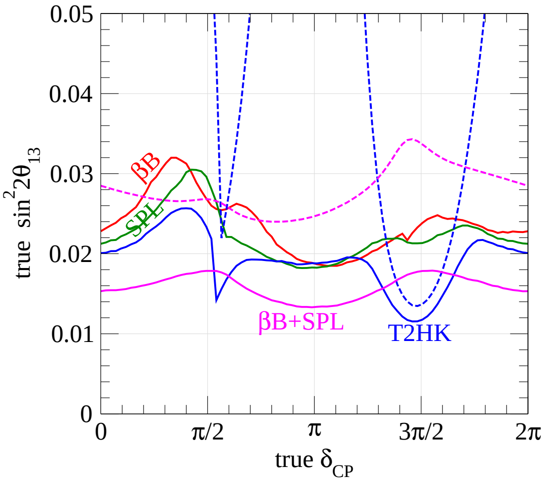

Fig. 9: Sensitivity to the mass hierarchy at 2 σ as a function of the true values of $\sin^2 2\theta_{13}$ and δ_{CP} without (dotted lines) and with (solid lines) combination with atmospheric neutrino measurements.

5.4 New Studies

New studies on SPL Super Beam have been started in the EUROν framework in order to optimize the physics performance of the project.

In these new studies, the possibility to use a liquid mercury target has been abandoned for the reasons already explained. A carbon target combined with a MiniBooNE like horn (Fig. 10) has been considered [29]. The length of the carbon target has been increased (78 cm) compared to the mercury one (30 cm) previously considered in order to have the equivalent of 2 interaction lengths in both cases.

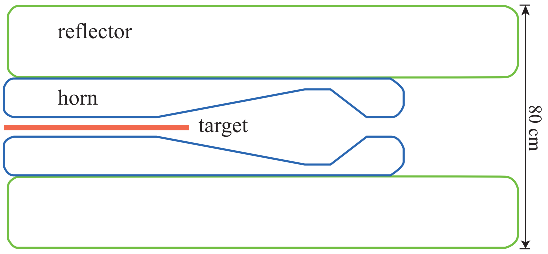

Fig. 10: New horn design using carbon target.

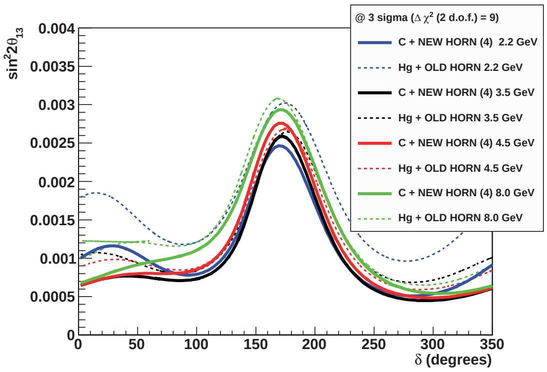

Fig. 11: $\sin^2 2\theta_{13}$ sensitivity with new horn versus δ_{CP} for different targets, mercury (30 cm) and carbon (78 cm).

The very first results are very promising demonstrating that there is still room for improvement by just optimizing the horn system. Fig. 11 shows a comparison between all already studied options (mercury, carbon) for several proton driver energies (2.2, 3.5, 4.5 and 8 GeV). The best performance is obtained with the new horn for 3.5 GeV proton energy. On top of the much easier handling, the utilization of a carbon target compared to the mercury one reduces the neutron flux by a factor of 15 decreasing significantly the risk of radiation damages.

6 Conclusions

The possibilities of constructing conventional high intensity neutrino beams in Europe are mainly concentrated around CERN.

The option of increasing the performance of existing facilities like the CNGS is very limited, mainly compromised by the fact that during the construction the passage to high power facility has not been foreseen. Also, the required intensity seems not to be reachable without major investment.

The upgrade of the CERN accelerator complex, mainly to satisfy the SLHC requirements, is very expected by the european neutrino community. These new facilities could provide high power proton beams which could be used to produce high intensity neutrino beams.

The present design of the PS2, suppose to replace the PS, could give a neutrino beam with an intensity of at least 4 times lower than the required one to be competitive. The High Power SPL could provide more than 4 MW proton beam opening new possibilities for low energy neutrino beams. This will give the possibility to observe for the first time CP violation in the leptonic sector. This facility has a big synergy with the CERN and DESY Beta Beam projects.

The european EUROν Design Study finishing in 2012 will study and compare (physics performance, technological risks, cost, timescale) the main european facility proposals, while the second european Design Study LAGUNA finishing next year, studies and compares the detection technics and underground possible sites to host large neutrino detectors.

In 2012–2013 the particle physics community will be ready to take decisions about the construction of new facilities mainly those concerning the LHC upgrade. It is important at that time to preserve the possibility of upgrading these new installations to high power facilities mainly to produce high intensity neutrino beams.

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