Letter of Intent for the VILLARS 2004 SPSC workshop

Discovery potential for a SPL/super beam and beta beam from CERN pointing at a Megaton class detector in the Fréjus area

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The discovery of neutrino oscillation both in the atmospheric and the solar sectors is one of the major achievements in high energy physics in the past 20 years. The discovery era in neutrino oscillations is not yet ended since three parameters still have to be measured: the mixing angle θ_{13} the ordering of the neutrino mass eigenstates (that can be expressed as sign(Δm^2)) and the CP-violating phase δ.

The first of these parameters sets the amplitude of the processes that can be used to measure the other two, while the third parameter, δ, opens the exciting possibility to measure processes that violate CP in the leptonic sector. All these parameters are fundamental parameters of the standard model and there is a wide and deep belief that the very small neutrino masses are related to a very high energy scale, not reachable at any accelerator. Furthermore CP violation by neutrinos could be one of the most important missing pieces to understand why the universe is composed solely by matter and not by antimatter.

A fierce competition at the international level exists in the efforts of measuring those parameters and the experiment that will lead the race in this field in the next years will be T2K in Japan (1) , having the capability of improving the sensitivity on θ_{13} by a factor 20 with respect to the present experimental limit (derived by the Chooz experiment: $\sin^2(2\theta_{13}) \geqslant 0.14$) . Nominally T2K will reach a sensitivity of $\sin^2(2\theta_{13}) \geqslant 0.006$ at 90% CL, in 5 years, starting data taking in 2009.

We think that Europe can enter this competition only through projects that can improve by about one order of magnitude the sensitivity of T2K in a time scale of 10 years. And only at this level of sensitivity processes that violate leptonic CP could be detected.

Two neutrino beams have been studied to this purposes at CERN (2), (3), a conventional neutrino beam generated by the Superconducting Proton Linac (SPL) (4), the SPL-SuperBeam, and an innovative neutrino beam, based on the decay of radioactive ions accelerated by the SPS, the Beta-Beam (5), (6). The latter offers the unique possibility of generate ν_e and anti-ν_e neutrino beam virtually free from intrinsic backgrounds and systematic errors.

Both neutrino beams have an average energy of about 300 MeV, so they can be detected by the same detector at a baseline of about 150 km. At these energies water can offer very good performances both in terms of signal efficiency and background rejection with the possibility to build detectors of mass of the order of one megaton.

The investments on a detector of total mass of about 650 kton to 1 Megaton, in a novel laboratory in the Fréjus area, would maximise the reach of the CERN beams and could bring in Europe the leadership on neutrino oscillation experiments. Furthermore such a detector would be an extraordinary facility in terms of proton decay searches, supernovae neutrinos, relic supernovae neutrinos, atmospheric and solar neutrinos (see the attached appendix).

In terms of sensitivity to θ_{13} , such a detector could improve by a factor 5 the T2K sensitivity measuring ν_e appearance in the ν_μ SPL-SuperBeam neutrinos (7), by a factor 8 when using the Beta-Beam (ν_μ appearance in a ν_e beam) (8) and by a factor 9 combining the two beams (see figure 1) . These sensitivities are computed for 5 years data taking.

In terms of discovery potential of the CP phase δ, the megaton detector could discover δ different from zero at 3 standard deviations if $\delta > 34°$ for any value of $\theta_{13} > 3°$ with the SPL SuperBeam (7) , $\delta > 34°$ for $\theta_{13} > 1.5°$ with the Beta-Beams (8) and $\delta > 22°$for $\theta_{13} > 1°$ for their combination (see figure 2). These discovery potentials are computed for 10 years of data taking; in the case of SPL-SuperBeam this running time should be shared in 2 years of ν_μ and 8 years of anti-ν_μ data taking to compensate the difference in cross sections.

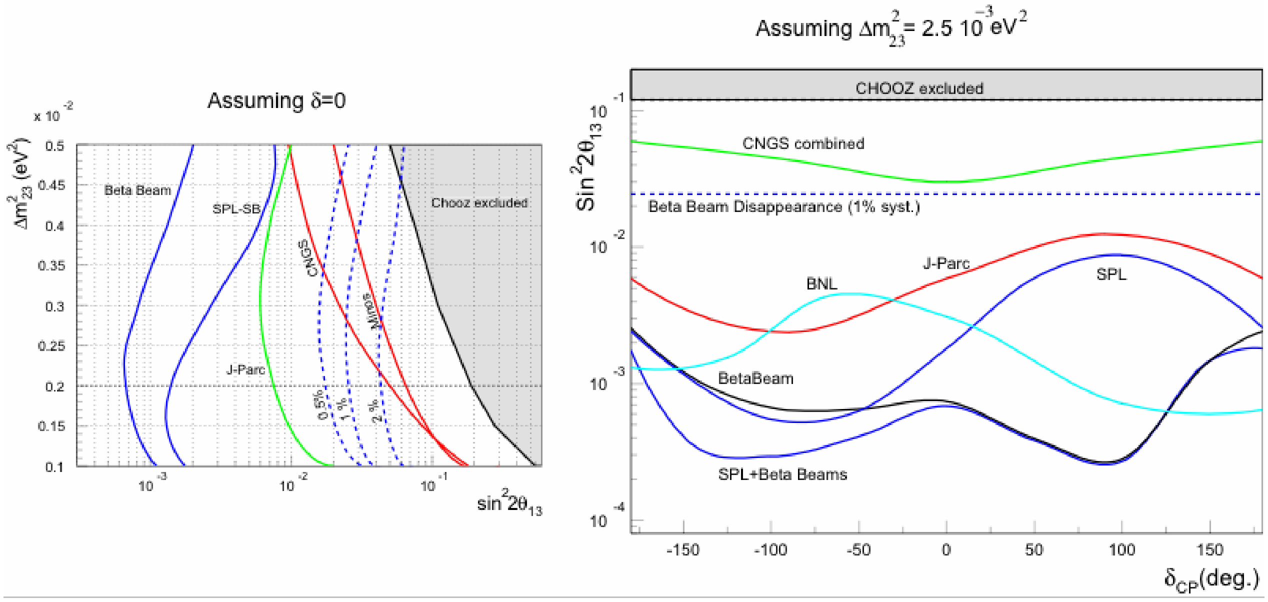

Figure 1. Sensitivity reach for θ_{13}, at zero (left) and variable (right) CP violating phase δ

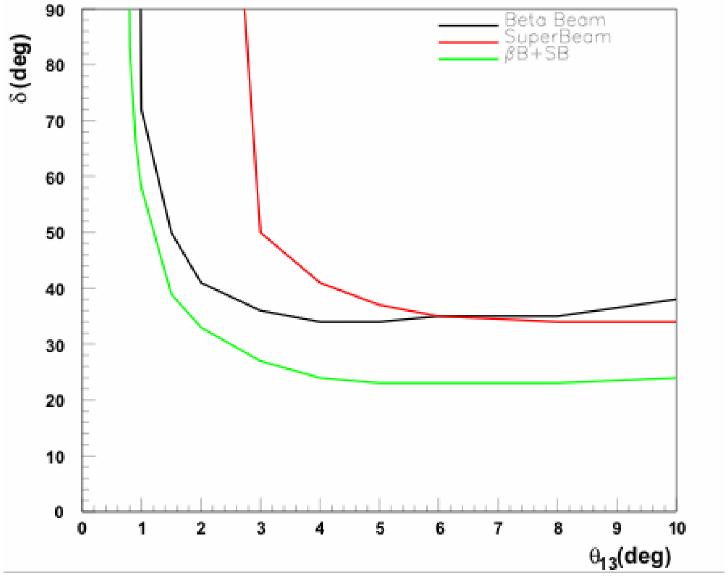

Figure 2 Sensitivity reach for 3 s discovery of a CP violating phase δ as a function of θ_{13}

Furthermore the combination of the ν_μ and anti-ν_μ beams of the SPL-SuperBeam with the ν_e and anti-ν_e neutrino ν_e and anti-ν_e beams of the Beta-Beams could allow for searches of CP, T, and CPT violating effects, and could produce signals with a muon in the final state with backgrounds coming from pions generated in NC events (the Beta Beam case), and signals with an electron in the final state with backgrounds from π^0 (the SuperBeam case), a very powerful handle to validate any experimental result.

The above sensitivities outperform those computed for the JParc phase II SuperBeam (9) and for the BNL SuperBeam (10), both computed with a very similar detector.

In relation to one of the requests of the SPSC committee concerning the optimal energy for the SPL beam figure 3 shows the preliminary results of a paper in preparation (11) studying the reach in θ_{13} for 3 proton energy options of the SPL. The 4.5 GeV option seems to be preferred. The definitive result will be reported in Villars.

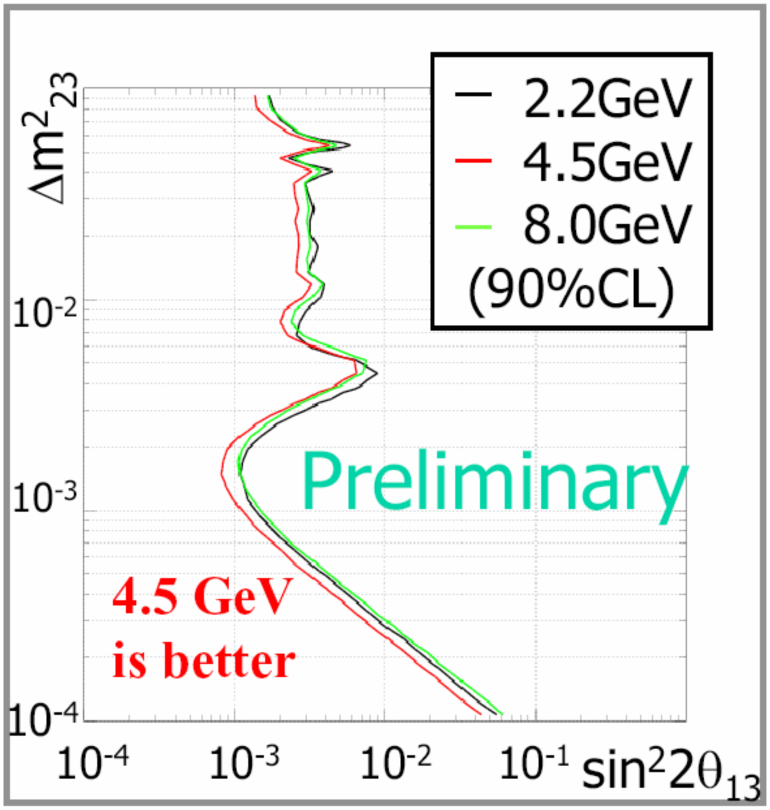

Figure 3 Reach in θ_{13} for 3 SPL energy options

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APPENDIX

Brief description of the site, the detector and the non-accelerator physics potential

The site

An intense activity of tunnel excavation will take place in the Fréjus area during the next few years and in particular **a** safety tunnel parallel to the Fréjus road tunnel, at the French-Italian boarder, was approved in December 2001 and its excavation should start at the beginning of the next year (2005). The diameter of this tunnel, with a present nominal value of about 5.5 m, is currently in the final stage of negotiation between the French and Italian Transport authorities . A series of 34 bypasses will connect the safety tunnel to the road tunnel. The end of the construction of the safety tunnel (without the bypasses) is planned around 2008-2009. This situation creates the opportunity to build a very large cavern near the existing laboratory LSM ("Laboratoire Souterrain de Modane") half way, 6.5 km -from both the French and the Italian entry of the tunnel. A laboratory at this location has the advantage of double horizontal access, large depth (4800 mwe), good quality of the rock (hardness and absence of water problems) and strong support from the local authorities (Regions Rhône-Alpes and Piemonte) and the Fréjus Tunnel Companies. Its major current difficulty is the perception of a possible conflict with the functionality of the safety tunnel on the French Transport Authority side. In the case this is confirmed the transport authorities recommend the excavation of a third separate tunnel to reach the area of the construction of the cavity (and evacuate the rock of the excavation), while the access after the construction could be done through the safety tunnel. This extra tunnel would of course increase the cost of the installation (cavity plus detector) by 10 to 20%. It is also interesting to note that the beam associated and proton decay physics potential are not seriously affected by moving to a shallower region and therefore reducing the extra excavation costs. There is, for instance, at 3km from the French entrance an overburden of 2500 mwe. In conclusion this is the preferred site and studies of feasibility and functional compatibilities are in progress. A more prospective scenario considers the opportunity created by the Lyon-Turin TGV 52 Km long tunnel crossing the Fréjus region.

The detector

The European groups considering a megaton class water cherenkov detector have not yet produced an independent study of its design. Nevertheless they work in close collaboration with the teams preparing two alternative designs of such a detector: the HyperKamiokande design and the UNO design. A feasibility study will be launched in Autumn 2004 , to examine their engineering compatibility with the possible sites in the Fréjus area.

The Japanese lead Hyperkamiokande (HK) design is an extrapolation the SuperKamiokande design, consisting of two ensembles of 5 cylindrical modules each, with the axis parallel to the ground, of dimensions 50x50x50 m^3, presenting a fiducial volume of 540 ktons and a coverage of 40% by 200000 photomultpliers (two 20inch PM/m^2). The HK detector could be installed at the Tochibora mine at a depth of about 1600 mwe and coupled with the JPARC accelerator, upgraded to about 4 MW of protons on the target to produce a very high intensity neutrino beam towards the detector at a distance of about 300 km. Its shallow depth clearly disfavors precision supernova and solar neutrino studies.

The US lead UNO collaboration proposes a detector consisting of 3 cubes of 60x60x60 m^3, densely instrumented in the middle cube (40%), sparsely in the two others (10%), arriving at a fiducial volume of 440 kilotons, and of the order of 70.000 photomultipliers. The currently favoured site by the UNO collaboration is the Henderson mine (Colorado) at a depth of about 4000 mwe. Two possible accelerator sites could be coupled in the USA to UNO : Fermilab and Brookhaven. The distance between these accelerator sites and the Henderson mine are 1500 km and 2750 Km respectively, much more adapted to a neutrino-factory scenario (or a high-energy beta-beam) then for a super-beam or a low-energy beta-beam strategy, though an ambitious study using the secondary minima of oscillation and trying to beat the large backgrounds is in progress.

Clearly the main challenges in the construction of a megaton class detector are

a) the engineering challenge of the construction of the megacubic-meter cavity and detector at an affordable cost and

b) the massive production of cheap large surface photodetectors with large (above 10 year) mean time between failures.

An example of the criticality of these two topics is the preliminary cost study of UNO, where out of the 400 Meuros needed for the detector construction, 180 Meuros are needed for the photodetector system and the associated electronics and 150 Meuros for the cavity excavation. The three regional groups (US, Japan and Europe) are exchanging information and promote R+D on these subjects.

A realistic timescale for the detector construction could be the following:

- Start in 2005 a 3 year R+D and site specification program in order to prepare a TDR by 2008.
- Assuming approval for the SPL and the Megaton detector in 2008, start a 4 year cavity excavation and a 6 year photodetector production program.
- The detector installation (first module) could start by 2012 and last for 2 to 3 years, while taking non-accelerator data.
- The full detector could accept a beam from CERN around 2015.

The non-accelerator physics potential

A megaton class detector has an extremely rich potential beyond the accelerator program that could justify its construction by itself. Further, a rich synergy can be developed between accelerator and non-accelerator aspects in the context of the study of unified theories (neutrino mass and proton decay) and their cosmological implications (matter-anti matter asymmetry, supernova physics, star and galaxy formation) The main topics of non-accelerator physics in order of importance, as seen in 2004, are the following:

1) **Proton decay:**

A UNO like detector will extend the lifetime sensitivity for proton decay in the $e\pi^0$ channel in the 10^{35} years range and the supersymmetry favoured νK in the 10^{34} years range; that is an order of magnitude better that SuperK (see JK Jung talk in NU 2004). The depth of the detector is not too critical for these searches. One expects of the order of 2 events of background per Megaton year for a 44% detection efficiency, or 0.15 events per Megaton year and 17% efficiency. The strategy depends on the available Mton years of statistics.

2) **Supernova neutrinos:**

In the case of a supernova explosion in our galaxy (frequency 3 per century) that is at an average distance of 10 kpc a UNO type detector will detect of the order of 140000 events, whose time structure and energy spectrum are obviously a mine of information on the core collapse mechanism, the possible black hole formation and will give very important measurements/constraints on θ_{13} and the mass hierarchy. The large mass of the detector extends the reach to 1 Megaparsec covering the local group of galaxies (mainly Andromeda) , doubling the frequency of possible detection (1 every 10 to 15 years).

But most important is the measurement of the Supernova Neutrino Relics (SNR), or Diffuse Supernova Background, that is the sum of supernova neutrinos integrated over redshift and sky directions. This measurement of utmost astrophysical and cosmological importance giving access to the star formation rate, galaxy evolution and cosmological parameters of the Universe has been pioneered by Kamioka and SuperKamioka. The current limit of SuperK (<1.2 anti- νe /cmsec) is only a factor 3 above the most pessimistic theoretical prediction (see M. Malek's SuperK thesis). The SNR measurement is background limited. The main reducible background is spallation from cosmic rays. One needs 40 years of SuperK running to obtain the factor 3 in sensitivity gain needed. A UNO type detector with an overburden of 4000 mwe, would have a cosmic ray spallation background two times lower than SuperK and would be able to exclude all models in 3-5 years or discover the effect. For these studies the deeper is the better, and below 1900 mwe (e.g. in the Tochibora mine) it becomes extremely difficult.

3) **Atmospheric neutrinos:**

A large statistics (4 UNO years) atmospheric neutrino study would give a below 5% measurement of Δm^2_{32} and $\sin^2 2\theta_{23}$ @ 90% CL, where the oscillation dip would be seen with high statistics (see T. Kajita talk in NOON2004). This measurement not competing with a measurement with a neutrino beam, unless Δm^2 is very low (below 0.002 eV^2). Global fits to three generation mixing will establish new limits in sterile neutrinos. One upcoming nutau CC event/ktonyear is expected through the oscillation of numu neutrinos, so one expects of the order of 440 events per year in a UNO-like detector. Consistency checks with the beam appearance experiments will be possible.

Probably the most interesting atmospheric signal is the electron appearance and stronger muon disappearance in the 5-10 GeV range in upward going events, passing through the earth core (Bernabeu/Ruiz/Petcov hep-ph0305152 but also Peres/Smirnov hep-ph0309312). They could lift the θ_{23} quadrant degeneracy ($\sin^2\theta_{23}$ higher or lower than 0.5) provided that θ_{13} is sufficiently high. One thus could obtain up to 3 σ excess in one year for $\sin^2\theta_{23} > 0.5$ and $\sin^2 \theta_{13} > 0.01$, but have no excess for any value of θ_{13} for $\sin^2\theta_{23} = 0.35$. The mass hierarchy also affects the result since it alters the percentage of νe and anti-νe composition. Normal mass hierarchy gives a stronger excess than the inverted one.

4) **Solar neutrinos :**

One expects 30000 solar events per year in an UNO like detector. The 20-fold increase in the statistics with respect to SuperK, will permit to study the effect of the oscillation on the energy spectrum (see Suzuki talk in Nu 2004). In particular an upturn of the LMA ^8B spectrum towards the lowest part is expected. Its measurement will constrain further Δm^2_{12} and $\sin^2\theta_{12}$. One also expects a 1-2% Day-Night effect, a characteristic signal of matter (MSW) effects. A 4-5 σ signal could be seen in a few years provided one achieves a 0.4% systematic error. Finally the increase of statistics will permit to detect or set sensitive limits on time variations in the neutrino flux from the sun interior.

5) **Astrophysical neutrinos:**

The domain of the high energy neutrino detection from astrophysical sources (Active Galactic Nuclei, Gamma Ray Bursts, WIMP annihilations) is usually studied in the framework of the new generation of neutrino telescopes in the multiTeV range where the astrophysical flux is above the atmospheric neutrino background. Water Cherenkov detectors of the kton and Megaton size can capitalize on pointing and time correlation of neutrinos and upcoming muons with transient phenomena to explore the same subject the multiGeV region SuperK has produced a series of interesting limits on most astrophysical processes. Surprises may accompany the 20-fold increase in sensitivity.

6) Physics potential with the Gd doping option

Beacom and Vagins proposed recently (hep-ph 0309300) the concept of a $GdCl_3$ doped (0.2%) water cherenkov detector, making neutrons detectable and therefore a Reines antineutrino double signature (positron + neutron) possible. This fresh idea is currently under intense scrutiny and R+D efforts concerning the radiopurity and transparency of the mixture and its properties of ageing and aggressiveness towards meterials. Since one is facing a 10 year interval before the detector enters in operation, enough for a full evaluation of its technical feasiblity, it is not unreasonable to consider the physics potential of such an option.

The first notable effect is the lowering of the threshold of antineutrino supernova detection, by reducing considerably the spallation background. One thus obtains as many as 40 SNR events /year for the most pessimistic scenario in an UNO like detector.

The second notable effect is the fact that it effectively turns a UNO-like detector to a Super KAMLAND with respect to the reactor antineutrinos, by lowering the detection threshold to around 3 MeV. A UNO type detector will obtain a two orders of magnitude increase in statistics, with respect to KAMLAND, but inferior energy resolution. Half a year of an UNO-like Gd doped detector with reactor neutrinos would give a precision on Δm^2_{12} below 1%, and $\sin^2\theta_{12}$ below 6%. The ultimate precision estimate needs to be studied further.

One can conclude that even a one or two years run of a $GdCl_3$ doped detector, conservatively scheduled after the conclusion of the physics program with the pure water option could have a large impact on neutrino physics and astrophysics.