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Superbeam Studies at CERN

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Abstract

A conventional low energy neutrino beam of great intensity could be produced by the Super Proton Linac at CERN as a first stage of a Neutrino Factory. Water Čerenkov and liquid scintillator detectors are studied as possible candidates for a neutrino oscillation experiment which could improve our current knowledge of the atmospheric parameters Δm^2_{atm}, θ_{23} and measure or severely constrain θ_{13}. It is also shown that a very large water detector could eventually observe leptonic CP violation.

1 The SPL neutrino beam

The planned Super Proton Linac (SPL) is a 2.2 GeV proton beam of 4 MW power [1] which could be used as a first stage of the Neutrino Factory complex at CERN[2]. It would work with a repetition rate of 75 Hz delivering $1.5 \cdot 10^{14}$ protons per pulse (10^{23} protons on target (pot) in a 10^7 s conventional year). Pions are produced by the interactions of the 2.2 GeV proton beam with a liquid mercury target and focused with a magnetic horn [3]. Target and horn assumed in the following are precisely those studied for the Neutrino Factory and no optimization has been attempted for this Superbeam.
Pions next transverse a cylindrical decay tunnel of 1 meter radius and 20

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Table 1
The SPL neutrino fluxes, for π^+(left) and π^-(right) focused in the horn, computed at 50 km from the target.

π^+ focused beam				π^- focused beam			
Flavor	Absolute Flux ($\nu/10^{23}$pot/m^2)	Relative (%)	$\langle E_\nu \rangle$ (GeV)	Flavor	Absolute Flux ($\nu/10^{23}$pot/m^2)	Relative (%)	$\langle E_\nu \rangle$ (GeV)
ν_μ	$1.7 \cdot 10^{12}$	100	0.26	$\overline{\nu}_\mu$	$1.1 \cdot 10^{12}$	100	0.23
$\overline{\nu}_\mu$	$4.1 \cdot 10^{10}$	2.4	0.24	ν_μ	$6.3 \cdot 10^{10}$	5.7	0.25
ν_e	$6.1 \cdot 10^{9}$	0.36	0.24	$\overline{\nu}_e$	$4.3 \cdot 10^{9}$	3.9	0.25
$\overline{\nu}_e$	$1.0 \cdot 10^{8}$	0.006	0.29	ν_e	$1.6 \cdot 10^{8}$	0.15	0.29

meters length. These dimensions have been optimized in order to keep the ν_e contribution low and ν_μ flux as high as possible.
We have used the `MARS` program[4] to generate and track pions. We have added polarization effects on μ decays and used analytical calculations to follow π and μ decays and particle trajectories [5].
The resulting neutrino spectra are shown in Fig. 1 and Table reftab:fluxes.

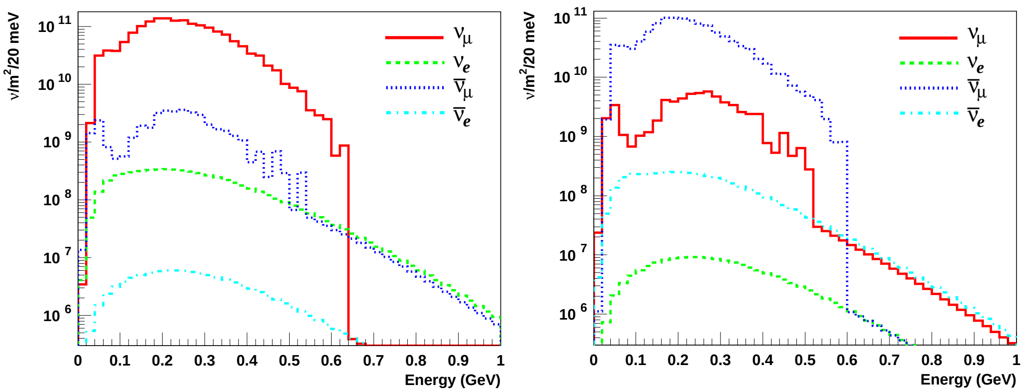

Fig. 1. *The SPL neutrino spectra, for π^+(left) and π^-(right) focused in the horn, computed at 50 km from the target.*

The average energy of the neutrinos is around 250 MeV with a ν_e contamination of $\sim 0.4\%$.
ν_e in the beam can be produced only by μ decays, since center-of-mass energy is below kaon production. ν_μ and ν_e come from the same decay chain $\pi^+ \to \nu_\mu \mu^+ \to e^+ \nu_e \overline{\nu}_\mu$ and so ν_e can be predicted by a direct measure of the ν_μ themselves. We estimate that combining the measurement of ν_μ interaction rate at the far detector with the ν_μ and ν_e rates in a close detector (0.5 kton at 1 km from the target), the ν_e contamination can be established with 2% systematic and statistical errors.

2 Detector scenarios

Fig. 2 shows the oscillation probability $P(\nu_\mu \to \nu_e)$ as a function of the distance. Notice that the first maximum of the oscillation at $L \sim 130$ km matches

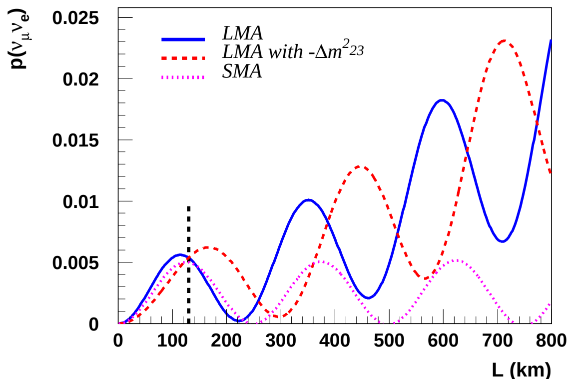

Fig. 2. $P(\nu_\mu \to \nu_e)$ *computed for* $\langle E_{\nu_\mu}\rangle = 0.26\ GeV$, $\Delta m^2_{atm} = 2.5 \cdot 10^{-3} eV^2$, $\Delta m^2_{sun} = 5 \cdot 10^{-5}$, $6 \cdot 10^{-6}\ eV^2$, $\pm\Delta m^2_{23}$, $\sin^2\theta_{13} = 0.01$, $\delta = 0$.

the distance between CERN and the Modane laboratory in the Frejus tunnel, where one could conceivably locate a large neutrino detector[6].

Detection of low-energy neutrinos at $O(100km)$ from the source requires a massive target with high efficiency. Moreover, a search for ν_e appearance demands excellent rejection of physics backgrounds, namely μ misidentification and neutral current π^0 production, which should be controlled to a lower level than the irreducible beam-induced background.

Backgrounds from atmospheric neutrinos remain negligible if the accumulator foreseen in the Neutrino Factory complex is used; it provides a duty cycle of 4000.

In this paper we consider two detector technologies, which have demonstrated excellent performance in the low energy regime, while being able to provide massive targets. These are, water Čerenkov detectors, as used in Super-Kamiokande[7], and diluted liquid scintillator detectors as used by the LSND experiment[8] and planned for the forthcoming MiniBoone experiment[9], where both Čerenkov and scintillation light are measured.

2.1 Water Čerenkov detectors

We have considered an apparatus of 40 kton fiducial mass and sensitivity identical to the Super-Kamiokande experiment. The response of the detector to the neutrino beam discussed in section 1 was studied using the NUANCE[10] neutrino physics generator and detector simulation and reconstruction algorithms developed for the Super-Kamiokande atmospheric neutrino analysis. These algorithms, and their agreement with real neutrino data, have been described elsewhere[7,11,12].

The SuperKamiokande standard algorithms for μ/e separation are very effective in the SPL-SuperBeam energy regime. [a]

Events with a π^0 are easily rejected in events where the two rings are found by a standard π^0 search algorithm, á la Super-Kamiokande. To reject events where only one γ has been initially identified, an algorithm[14] forces the identification of a candidate for a second ring, which, if the primary ring is truly a single electron, is typically either very low energy, or extremely forward. By requiring that the invariant mass formed by the primary and the secondary rings is less than $45\,\mathrm{MeV}/c^2$, almost all remaining π^0 contamination is removed. Being the SPL-SuperBeam more clean and at lower energies than the beam of Ref. [15], we have not attempted to introduce more aggressive π°rejection algorithms.

Data reduction is summarized in Table 2. Contamination by the intrinsic beam ν_e is dominant.

Table 2

Summary of simulated data samples a π^+ and π^- focused neutrino beams. The numbers in the rightmost column (after all cuts) represent the sample used to estimate the oscillation sensitivity.

Channel	Initial sample	Visible events	Fit in fid. vol. Single-ring $100-450\,\mathrm{MeV/c^2}$	Tight particle ID	No $\mu\to e$	$m_{\gamma\gamma} \leq 45\,\mathrm{MeV/c^2}$
π^+ focused beam						
ν_μ	3250	887	578.4	5.5	2.5	1.5
ν_e	18	12.	8.2	8.0	8.0	7.8
NC	2887	36.9	8.7	7.7	7.7	1.7
$\nu_\mu\to\nu_e$	100%	82.4%	77.2%	76.5%	70.7%	70.5%
π^- focused beam						
$\overline{\nu}_\mu$	539	186	123	2.3	0.7	0.7
$\overline{\nu}_e$	4	3.3	3	2.7	2.7	2.7
NC	687	11.7	3.3	3	3	0.3
$\overline{\nu}_\mu\to\overline{\nu}_e$	100%	79.3%	74.1%	74.0%	67.1%	67.0%

2.2 Liquid scintillator detectors

The energy range (50 MeV-1 GeV) and the rejections against background needed by MiniBoone nicely match the requirements of our study. Neutrino-^{12}C cross sections are taken from reference[16]. [b]

Table 3 shows data reduction assuming no ν_μ-ν_e oscillation, for a 200 kton-

[a] We have only tightened the cut value of the particle identification criterium, which is based on a maximum likelihood fit of both μ-like and e-like hypotheses (P_μ and P_e respectively). We use $P_e > P_\mu + 1$ instead of the default $P_e > P_\mu$.

[b] They come from an upgraded version of the continuous random phase approximation method and in average they are lower by about $\sim 15\%$ from what quoted by the MiniBoone experiment.

Table 3

Summary of data samples in a 40 kton liquid scintillator detector at $L = 130$ km for a 200 kton/year exposure.

π^+ focused beam			π^- focused beam		
Channel	Initial sample	Final sample	Channel	Initial sample	Final sample
ν_μ^{CC}	2538	2.5	$\overline{\nu}_\mu^{CC}$	451	0.5
ν_e^{CC}	12	6	$\overline{\nu}_e{}^{CC}$	2.3	1.0
NC (visible)	48	0.5	NC	10	< 0.1
$\nu_\mu \to \nu_e$	100%	50%	$\overline{\nu}_\mu \to \overline{\nu}_e$	100%	50 %

year exposure. As before, intrinsic beam ν_e contamination results to be the dominant background.

As one can see comparing Tables 2 and 3 the performances of both devices are quite similar. The conclusion is that one would prefer for this experiment a water detector, where truly gargantuan sizes can be afforded.

3 Physics Potential

3.1 Sensitivity to the atmospheric parameters

To illustrate the precision in measuring δm^2_{atm} and θ_{23} Fig. 3 shows the result of a 200 kton-years exposure ν_μ disappearance experiment on a liquid scintillator detector. The computation is performed defining 4 energy bins in the 0.1-0.7 GeV energy range and including Fermi motion, that is by far the most limiting factor to energy reconstruction at these energies. See[17] for more details. We find that Δm^2_{23} can be measured with a standard deviation of $1 \cdot 10^{-4}$ eV^2/c^4 while $\sin^2 2\theta_{23}$ is measured at the $\sim 1\%$ precision level.
In case of water Čerenkov, the first energy bin would be lost, being the μ below threshold. In this case the resolution on the atmospheric parameters is slightly worsened, especially in case of low Δm^2.

3.2 Sensitivity to θ_{13}

The different solar solutions don't affect very much $P(\nu_\mu \to \nu_e)$ for $L = 130$ km as can be seen in Fig.2. We will use SMA parameters, a hierarchical mass model, $\delta = 0$. Given the low statistic and the poor energy resolution we consider in this case a counting experiment, not exploiting spectral distortions. Fig. 3(right) shows the expected sensitivity for a 5-year run with a 40 kton (400 kton) water target at a distance of 130 km.
The sensitivity of this search results to be about 15 (60) times higher than the present experimental limit of $\sin^2 \theta_{13}$ coming from the Chooz experiment[18].

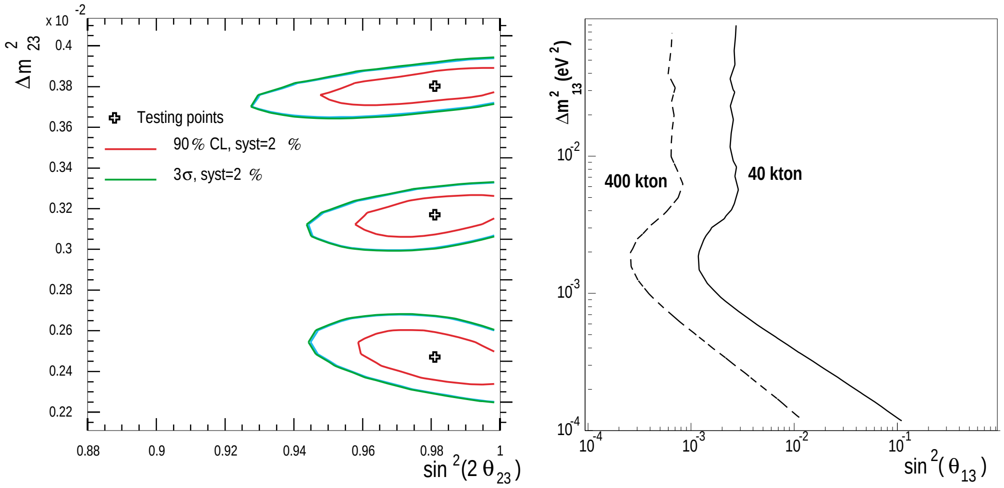

Fig. 3. *LEFT: Fits of* $\delta m^2_{atm}(eV^2)$*,*$\sin^2(2\theta_{23})$ *after a 200 kton/year exposure,* $L = 130km$*, 2% systematic errors. The crosses sign the initial points* $(0.98, 3.8 \cdot 10^{-3})$, $(0.98, 3.2 \cdot 10^{-3})$, $(0.98, 2.5 \cdot 10^{-3})$ *in* δm^2_{atm}, $\sin^2(2\theta_{23})$ *coordinates. RIGHT:* $\nu_\mu \rightarrow \nu_e$ *oscillation sensitivity for* π^+ *focused neutrino beams with a 40 (400) kton detector.*

3.3 Sensitivity to CP in the LMA-MSW scenario

In the remaining of this section we will assume $\delta m^2_{12} = 10^{-4}$ eV^2 (in the upper part of LMA) and $\sin^2 2\theta_{12} = 1$.
The $\overline{\nu}_\mu + {}^{16}O$ cross-section is approximately six times less than that for $\nu + {}^{16}O$ at $E_\nu \simeq 0.25$ GeV; to compensate that we have considered a 10 year run with focused π^- and a 2 year run with focused π^+.
We follow the approach in[19,20] and fit simultaneously the number of detected electron-like events to the CP phase δ and θ_{13}. Notice that, although we apply a full three family treatment to our calculations, including matter effects, these are not important at the short distances and low energies considered. Fig. 4(left) shows the confidence level contours including statistical and background subtraction errors. A maximally violating CP phase ($\delta = \pm 90°$) would be just distinguishable from a non CP violating phase ($\delta = 0°$).
Fig. 4(right) shows the result of the same fit, now assuming a very large water detector, such as the proposed UNO[21], with a fiducial mass of 400 kton. Clearly, the prospects to observe CP violation are much improved.

4 Conclusions

We have examined the physics potential of a low energy Superbeam which could be produced by the CERN Super Proton Linac. Water Čerenkov and liquid oil scintillator detectors have been considered.

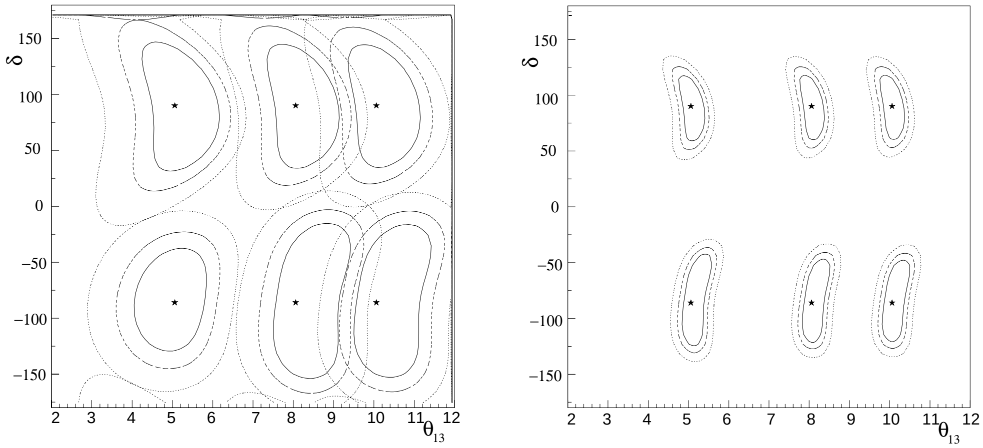

Fig. 4. 1σ, *90 %CL and 99 %CL intervals resulting from a simultaneous fit to the* θ_{13} *and* δ *parameters. The generated values were* $\theta_{13} = 5°, 8°, 10°$, $\delta = \pm 90°$. *Computed for a 10 year anti-neutrino and a 2 year neutrino run,* $L = 130$ *km with a 40 kton detector (left) or with a 400 kton detector (right).*

The low energy of the beam studied has several advantages. Beam systematics are kept low because 2.2 GeV protons are below the kaon production threshold. Furthermore, e/μ and e/π^0 separation in a water (liquid oil) detector is near optimal at these low energies. The drawback is the small anti neutrino cross section, which is more than a factor five smaller than neutrino cross section. These cross-sections are in addition quite uncertain and would certainly need to be measured.
The peak of the oscillation is at a distance of about 130 km where an ideal location exists, the Modane laboratory in the Frejus tunnel.
A "moderate" size detector ("only" twice as big a Super-Kamiokande) at this baseline could, in a five year run, improve the precision in the determination of the atmospheric parameters by about one order of magnitude (with respect to the expected precision of next generation neutrino experiments, such as Minos). It could also improve by more than one order of magnitude the sensitivity on $\sin^2\theta_{13}$ compared to the present experimental limits.
Such a detector could also, if the solution to the solar neutrino problem lies in the upper part of the LMA, detect a maximally violating CP phase. For CP violation studies a very large detector, á la UNO (400 kton fiducial mass), is mandatory.

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