Neutrino SuperBeams in Europe

Mauro Mezzetto [a]

[a]Istituto Nazionale Fisica Nucleare, Sezione di Padova. Via Marzolo 8, 35100 Padova, Italy.

A brief report of the developments in Europe towards next generation neutrino oscillation long baseline experiments capable of measuring the still unknown parameters θ_{13} and $\delta_{\rm CP}$.

1. Introduction

Three parameters are still unknown in neutrino oscillations: the mixing angle θ_{13} , the CP phase $\delta_{\rm CP}$ and the neutrino mass hierarchy parametrized by sign(δm^2_{23}) . They can be detected in a long baseline neutrino experiment looking for sub-leading $\nu_\mu \to \nu_e$ oscillations.

The first experiment optimized to those searches will be T2K [1], at the J-Parc 50 GeV, 0.75 MW proton synchrotron, scheduled to start in 2009, with a θ_{13} sensitivity 20 times better than the present experimental limit [2]. It could be complemented by the Noνa [3] experiment in the NuMi beam line and by the reactor experiment Double Chooz [4]. Even the combination of those three experiments however will not have any sensitivity to $\delta_{\rm CP}$ [5].

A new generation of experiments has to be designed to address the search of leptonic CP violation. It will be characterized by neutrino SuperBeams and/or Beta Beams.

Neutrino factories are designed to be the ultimate facility for neutrino oscillation searches, [6]. They will probably be ready in a longer timescale and they will not be discussed in this report.

In this paper are illustrated the studies done in Europe to address the needs of these future long baseline experiments. Most of these developments have been discussed inside the "Neutrino Oscillation Working Group" [7], a forum of discussion promoted by ECFA and recently endorsed by the european network BENE [8].

2. Sub-Leading $\nu_\mu \to \nu_e$ oscillations

The parameters θ_{13} , $\delta_{\rm CP}$ and sign(δm^2_{23}) can be extracted by measuring sub-leading $\nu_\mu \to \nu_e$ oscillations. For a parametrization of this probability see reference [9]. $\nu_\mu \to \nu_e$ oscillations have a leading term driven by the solar parameters, but at the baseline defined by δm^2_{23}, L_{atm}, they are driven by θ_{13} terms for $\sin^2 2\theta_{13} > 10^{-3}$.

θ_{13} searches look for experimental evidence that $P_{\nu_\mu\to\nu_e} > P_{\nu_\mu\to\nu_e}(\theta_{13} = 0)$ while leptonic CP violation searches look for $A_{CP} = \frac{P(\nu_\mu\to\nu_e)-P(\overline{\nu}_\mu\to\overline{\nu}_e)}{P(\nu_\mu\to\nu_e)+P(\overline{\nu}_\mu\to\overline{\nu}_e)} \neq 0$. This asymmetry results to be proportional to $1/\sin\theta_{13}$ while $P_{\nu_\mu\to\nu_e}$is proportional to $\sin^2 2\theta_{13}$, at the first order A_{CP} sensitivity is independent from θ_{13} , provided that θ_{13} is big enough to allow for a sizable $\nu_e(\overline{\nu}_e)$ signal. Matter effects also produce differences from $P_{\nu_\mu\to\nu_e}$and $P_{\overline{\nu}_\mu\to\overline{\nu}_e}$, they are proportional to the baseline and at 100 km they result to be negligible.

The richness of $\nu_\mu \to \nu_e$ transitions is also their weakness: it will be very difficult for pioneering experiments to extract the single values of all the parameters. Correlations are present between θ_{13} and $\delta_{\rm CP}$ and clone solutions exist in absence of information about sign(δm^2_{23}) and about the $\pi/2 - \theta_{23}$ ambiguity [10].

3. Neutrino SuperBeams

SuperBeams could be defined as conventional neutrino beams generated by a proton driver with more than 1 MW. At that power no conventional neutrino target could survive, so they will require R&D for the target design [11].

Pushed to those intensities conventional neutrino beams will hit their ultimate limitations, namely the presence of 4 neutrino flavors in the neutrino beam ($\nu_e, \overline{\nu}_\mu, \overline{\nu}_e$ besides the main neutrino component, ν_μ) and the difficulty to precisely predict fluxes and contaminations because of the lack of knowledge of secondary particle production cross sections.

SuperBeam experiments have been proposed in the States [3], [12], and in Japan [1]. This latter project, T2K phase II, probably the most powerful proposal, plans a machine upgrade from 0.75 MW to 4 MW fired to HyperKamiokande, a detector with a fiducial volume 24 times bigger than SuperKamiokande. Its physics potential has been discussed in [13] showing that $\delta_{\rm CP}$ can be detected at 3 σ if bigger than 20° and if θ_{13} is bigger than 2°. This θ_{13} range corresponds to the T2K phase I sensitivity. Sensitivity depends very much from the systematic errors level, systematic errors bigger than 2% would significantly degrade the experimental sensitivity.

3.1. Extensions of CNGS

CNGS neutrino beam has been optimized for ν_τ appearance, has a mean neutrino energy of 17 GeV and detectors at a baseline of 732 km (CERN-LNGS). This optimization is very different from a θ_{13} optimization, where for the same baseline the mean neutrino energy should be $\sim$ 1.5 GeV. Two studies have been done to re-use part of the existing infrastructure to build a neutrino beam optimized for θ_{13} searches. The study of reference [14] considers a new beam optics capable to produce a neutrino beam of 1.5 GeV mean energy fired to a 3 kton Icarus detector at Gran Sasso. The experiment would reach 1/3 of the sensitivity of T2K phase I in a 5 years run at the nominal CNGS intensity.

A second study considered a low energy neutrino beam (1.5 GeV mean energy) fired to a detector made of 44k phototubes deployed 1000 m underwater, equipping 2 Mton of water, 2° degrees off-axis, 1200 km from CERN (CNGT) [15]. In this case the detector would be placed at the second oscillation maximum and if movable it could take data both at the minimum and at the maximum of oscillation probability. Sensitivity would be marginally worse than T2K phase I, in a 5 years data taking [15].

These performances are similar to T2K phase I but the timescale would be significantly later: allowing for a 5 years run for the standard CNGS beam plus a couple of years for the beam modifications, these experiments could only start after the end of T2K data taking.

3.2. Beams from a 20-50 GeV high intensity synchrotron

A rapid cycling synchrotron with proton energy in the 20-50 GeV range, could be foreseen for the LHC luminosity upgrade. Such a machine would be very similar to the J-Parc 50 GeV, 0.75 MW proton synchrotron and could reach 4 MW.

Performances of a 3 kton liquid argon detector (with 100% efficiency, no detector backgrounds and no systematic errors) exposed to a neutrino beam produced by a 20 GeV, 6.5 MW proton driver (PS++) have been published in [16]. θ_{13} sensitivity would be similar to T2K phase I. With the known technologies no significant improvement from these performances can be foreseen in terms of detector mass times efficiency by a neutrino detector inside a LNGS hall (40000 m^3). Other experimental developments could overcome this limitation, such as high density calorimeters, surface detectors or new underground facilities. They haven't been studied yet.

3.3. SPL SuperBeam at CERN

The Super Proton Linac (SPL) is a proton driver designed to deliver 2mA of 2.2 GeV (kinetic energy) protons [17]. It could be the driver either of a Beta Beam or of a Neutrino Factory. Protons would be delivered to an accumulator, that could be hosted in the ISR tunnel, in order to have beam batches 23 ns long. Pions are produced by the interactions of the 2.2 GeV proton beam with a liquid mercury target [11] and focused with magnetic horns [18]. The resulting neutrino flux [18] has a neutrino energy $\langle E_\nu \rangle = 260 MeV$ and the optimal baseline would be of about 100 km.

There are several advantages by running at such small ν energies. Given the relatively short baseline, matter effects are negligible and don't compete with leptonic CP violating effects. Protons are below the kaon production threshold, reducing ν_e backgrounds and the incertitudes related to their estimation. π° rejection is favored thanks to the wide γs opening angle [1]. Charged

[1]Indeed better rejections than T2K (running at $\langle E_\nu \rangle \simeq$

current (CC) events are for the largest part quasi elastics, the event category best reconstructed in a water Čerenkov detector.

On the other hands cross sections are small at these energies and change very rapidly with energy. Antineutrino interaction rates are suppressed either because antineutrino/neutrino cross sections ratio is at a minimum: ($\simeq 1/4$) and because π^- hadroproduction is disfavored at 2.2 GeV, [2]. Fermi motion prevents an accurate event energy reconstruction. Atmospheric neutrino backgrounds are severe because of the high flux below 0.5 GeV and the limited rejection factor provided by the poor angular resolution; this is the reason why an accumulator is needed downstream the proton driver to keep the duty cycle low. Given the baseline, sign(δm^2_{23}) cannot be measured. It should be noted that CC rates generated by the SPL-SB at the optimal baseline, 41 CC events/kton/year, are smaller than T2K phase I rates, $\sim$ 100 events/kton/year, the driver of T2K (50 GeV) having 6 times less power.

SPL SuperBeam (SPL-SB) performances have been computed in [19] for a water Čerenkov detector, 440 kton fiducial (20 times SuperKamiokande) [20], 130 km from CERN, under the Frejus. Given the poor energy resolution a counting experiment has been evaluated, while it has been shown in a recent paper [21] that energy reconstruction may be used having beneficial effects. θ_{13} sensitivity is shown in Fig. 2, while $\delta_{\rm CP}$ discovery potential (3σ) is shown in Fig. 3. These plots don't take into account the sign(δm^2_{23}) and $\pi/2 - \theta_{23}$ ambiguities, for a computation of SPL-SB sensitivities having them included see reference [22].

SPL energy, 2.2 GeV, was originally fixed having in mind the re-usage of LEP RF cavities. More modern cavities could allow higher energies. In a recent paper [23], θ_{13} sensitivities as function of the proton beam energy, keeping fixed the power of the machine and the experimental baseline, have been computed. At an energy of 3.5 GeV, and focusing higher momentum pions, most of the weak points of the SPL-SB are cured: hadroproduction becomes more favorable and an higher energy neutrino beam can be produced ($\langle E_\mu \rangle \simeq 350$ MeV) allowing for a moderate energy binning (200 MeV/bin). CC interaction rate would be raised from 41 to 122 events/kton/year, [3]. Performances in this new configuration (SPL-SB 3.5GeV) are shown in Fig. 2 and 3. [4]

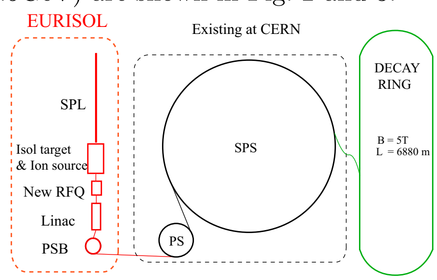

Figure 1. Schematic layout of the Beta Beam complex. At left, the low energy part is largely similar to the EURISOL project [29]. The central part (PS and SPS) uses existing facilities. At right, the decay ring has to be built.

4. Beta Beams

Beta Beams (βB) have been introduced by P. Zucchelli in 2001 [24]. The idea is to generate pure, well collimated and intense ν_e ($\overline{\nu}_e$) beams by producing, collecting, accelerating radioactive ions and storing them in a decay ring in 10 ns long bunches, to suppress the atmospheric neutrino backgrounds. This approach overcomes the limitations of conventional neutrino beams: βB would be virtually background free and fluxes could be easily computed by the properties of the beta decay of the parent ion and by its Lorentz boost factor γ.

The best ion candidates so far are ^{18}Ne and ^{6}He for ν_e and $\overline{\nu}_e$ respectively. A baseline study for a Beta Beam complex has been produced at CERN [25] and shown schematically in Fig. 1. In this scenario Beta Beam neutrino energies are below 0.5 GeV and the ideal technology would be again water Čerenkov.

0.8 GeV) can be obtained for signal efficiencies greater by about a factor 2.

[2] To compensate that, 2 years of ν_μ and 8 years of $\overline{\nu}_\mu$running must be planned for the leptonic CP violation searches.

[3] This improvement includes a longer (20m to 40m) and wider (1m diameter to 2m) decay tunnel.

[4] θ_{13} sensitivity of Fig. 2 is better than what quoted in [23] because it is computed taking into account the energy information.

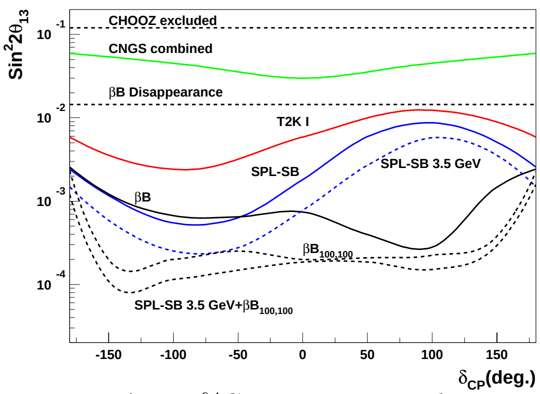

Figure 2. θ_{13} 90%CL sensitivity as function of $\delta_{\rm CP}$ for $\delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$, sign$(\delta m^2_{23}) = 1$, 2% systematic errors. CNGS and T2K curves are taken from [9], BNL from [12]. SPL-SB sensitivities have been computed for a 5 years ν_μ run, βB for a 5 years ν_e+ $\overline{\nu}_e$ run.

The reference βB fluxes are $2.9 \cdot 10^{18}$ ^{6}He useful decays/year and $1.1 \cdot 10^{18}$ ^{18}Ne decays/year. The SPS could accelerate ^{6}He ions at a maximum γ value of $\gamma_{^6\rm He} = 150$ and ^{18}Ne ions up to $\gamma_{^{18}\rm Ne} = 250$. In the baseline scenario the two ions circulate in the decay ring at the same time. This is feasible provided that their γ are in the ratio $\gamma_{^6\rm He}/\gamma_{^{18}\rm Ne} = 3/5$. The same fluxes can be obtained by running the two ions separately [26]. This allows a better optimization of the physics potential of the machine [27].

The baseline scenario physics potential has been computed in [28] for $\gamma_{^6\rm He} = 60$, $\gamma_{^{18}\rm Ne} = 100$, see Fig. 2 and 3. In the same plots performances computed with both ions at $\gamma = 100$, exploiting energy shape information (200 MeV/bin), are also displayed ($\beta\rm B_{100,100}$), with a clear gain in sensitivity. The overall optimization and the assesment of the physics potential of the baseline Beta Beam will be the argument of forthcoming papers. Sensitivities taking into account all the parameter degeneracies and ambiguities have been computed in [22].

βB and SPL-SB are perfectly compatible both in terms of SPL proton economics and in terms of optimal baseline. The same detector could then be exposed to 2×2 beams (ν_μ and $\overline{\nu}_\mu \times \nu_e$ and $\overline{\nu}_e$) having access to CP, T and CPT searches in the same run. Physics potential of this combination of beams is illustrated in Fig. 2 and 3.

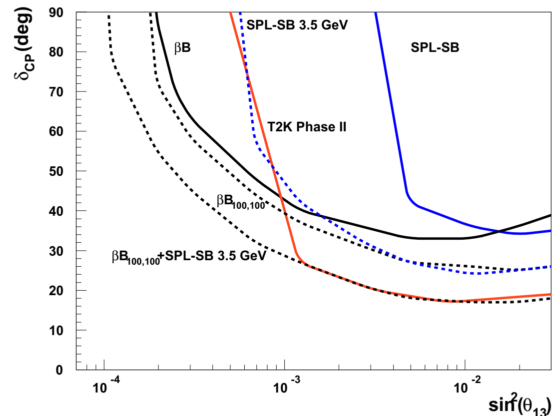

Figure 3. $\delta_{\rm CP}$ discovery potential at 3σ (see text) computed for a 10 years run, 2% systematic errors. T2K phase II curve is taken from [13].

Beta Beam capabilities for ions accelerated at higher energies than those allowed by SPS have been computed in [30], assuming that the same ion fluxes of the baseline scenario can be maintained. In particular accelerating ^{6}He ions up to $\gamma = 350$ and placing the megaton detector at about 700 km, θ_{13}, sign(δm^2_{23}) and $\delta_{\rm CP}$ sensitivities similar or better to those of a Neutrino Factory could be reached. Additional ideas about high energy Beta Beams have been published in [31]. For a review see also [27].

5. Conclusions

A summary of future long baseline experiments is in Tab. 1. The best candidates so far are Beta Beams, an approach virtually free from intrinsic backgrounds and systematics.

This project covers several important physics themes, ranging from the very deep synergies with EURISOL, aiming at producing high intensity radioactive beams for nuclear physics studies, to the excellent physics capabilities of the megaton water Čerenkov detector in its own [20].

Beta Beams could be complemented by a neutrino SuperBeam generated by the SPL 4MW, 2.2 GeV proton Linac fired to the same detector, allowing for CP and T violation searches as well as CPT violation in neutrino oscillations.

REFERENCES

1. Y. Itow *et al.*, hep-ex/0106019.

Table 1
Summary table of different LBL options. T2K phase II $\sin^2 2\theta_{13}$ sensitivity is extrapolated from T2K phase I. PS++ numbers are normalized to 4 MW power. Regarding βB, the $\nu_\mu{}^{CC}$ line indicates the sum of ν_e^{CC} and $\overline{\nu}_e^{CC}$ rates while the π/ν_e line indicates the fraction of NC backgrounds normalized to the non oscillated ν_e+ $\overline{\nu}_e$ rate.

		T2K	T2K 2	PS++	SPL	SPL 3.5	βB	βB$_{100,100}$
p-driver	(MW)	0.75	4	4	4	4	0.4	0.4
p beam energy	(GeV)	50	50	20	2.2	3.5	1-2.2	1-2.2
$\langle E(\nu_\mu)\rangle$	(GeV)	0.7	0.7	1.6	0.27	0.35	0.3	0.4
L	(Km)	295	295	732	130	130	130	130
Off-Axis		2^0	2^0	-	-	-	-	-
ν_μ^{CC} (ν_e^{CC}) (no oscillation)	(Kt/year)	100	500	450	41	122	38	56
ν_e^{CC}/ν_μ^{CC}	(%)	0.4	0.4	1.2	0.4	0.7	0	0
Detector Fid. Mass	(kton)	22.5	540	2.2	440	440	440	440
Material		H_2O	LAr	H_2O	H_2O	H_2O	H_2O	H_2O
Signal efficiency	(%)	40	40	100	70	70	60	70
π°/ν_e (π/ν_e)	(%)	80	80	0	30	30	0.2	0.2
$\sin^2 2\theta_{13}\cdot 10^4$	(90% CL)	60	6	64	18	7	7	2

2. M. Apollonio et al., Eur. Phys. J. C 27 (2003) 331, [hep-ex/0301017].
3. I. Ambats et al. [NOvA Collaboration], FERMILAB-PROPOSAL-0929
4. F. Ardellier et al., hep-ex/0405032.
5. P. Huber et al., hep-ph/0403068. K. B. McConnel and M. H. Shaevitz, hep-ex/0409028.
6. S. Geer, Phys. Rev. D 57 (1998) 6989 [Erratum-ibid. D 59 (1999) 039903], [hep-ph/9712290]. M. Apollonio et al., hep-ph/0210192.
7. Neutrino Oscillation Working Group, `http://axpd24.pd.infn.it/nowg`.
8. `http://bene.na.infn.it/`
9. P. Migliozzi and F. Terranova, Phys. Lett. B 563 (2003) 73, [hep-ph/0302274].
10. H. Minakata, H. Nunokawa and S. J. Parke, Phys. Rev. D 66 (2002) 093012 [hep-ph/0208163] and references therein.
11. H.D.Haseroth et at., AIP Proceedings 721, 48-59, 2003. M.S.Zisman, AIP Proceedings 721, 60-67, 2003.
12. M. V. Diwan et al., Phys. Rev. D 68, 012002 (2003), [hep-ph/0303081].
13. T. Kobayashi, J. Phys. G 29 (2003) 1493.
14. A. Rubbia and P. Sala, JHEP 0209 (2002) 004 [hep-ph/0207084].
15. A.E.Ball et al., CERN-SPSC-2004-025,SPSC-M-723, 21 September, 2004.
16. A. Ferrari, A. Rubbia, C. Rubbia and P. Sala, New J. Phys. 4 (2002) 88 [hep-ph/0208047].
17. B. Autin et al., CERN-2000-012
18. A. Blondel et al., CERN-NUFACT-53. S. Gilardoni et al., J. Phys. G 29 (2003) 1801.
19. J. J. Gomez-Cadenas et al., hep-ph/0105297. A. Blondel et al., Nucl. Instrum. Meth. A 503 (2001) 173. M. Mezzetto, J.Phys.G29:1771-1776, 2003; [hep-ex/0302005].
20. UNO Collaboration, hep-ex/0005046
21. A.Blondel et al., Nucl. Instrum. Meth. A 535 (2004) 665.
22. A. Donini et al., hep-ph/0406132. A. Donini et al., hep-ph/0411402.
23. J. E. Campagne and A. Cazes, hep-ex/0411062.
24. P. Zucchelli, Phys. Lett. B 532 (2002) 166.
25. B. Autin et al., physics/0306106. M. Benedikt, S. Hancock and M. Lindroos, Proceedings of EPAC, 2004, http://accelconf.web.cern.ch/AccelConf/e04
26. Mats Lindroos, private comunication.
27. M. Mezzetto, hep-ex/0410083.
28. M. Mezzetto, J.Phys.G29:1781-1784, 2003; [hep-ex/0302007]. J. Bouchez, M. Lindroos and M. Mezzetto, AIP conference proceedings, Vol. 721, 37-47, 2003. [hep-ex/0310059].
29. `http://www.ganil.fr/eurisol/`
30. J. Burguet-Castell at al., Nucl. Phys. B 695 (2004) 217 [hep-ph/0312068].
31. F. Terranova et al., hep-ph/0405081.