FUTURE NEUTRINO LONG BASELINE EXPERIMENTS*

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A new generation of reactor and accelerator neutrino oscillation experiments - Double Chooz, Daya Bay, Reno, T2K and NOνA — is ready to start a sensitive search for oscillation signals generated by the mixing parameter θ_{13}. Their output will be a fundamental milestone to optimize further experiments aimed at detecting CP violation in the neutrino sector, a key phenomenon with profound implications in particle physics and cosmology. Since late 90s, a world-wide activity is in progress to design facilities that can access CP violation in neutrino oscillation and perform high precision measurements of the lepton mixing matrix. In this paper the status of these studies will be summarized, focusing on the options that are best suited to exploit existing European facilities.

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1. Neutrino oscillations

The discovery of neutrino oscillations [1] has now established beyond doubt that neutrinos have mass and mix. This existence of neutrino masses is in fact the first solid experimental fact requiring physics beyond the Standard Model.

Neutrino oscillations are consistently described by three families ν_1, ν_2, ν_3 with mass values m_1, m_2 and m_3 that are connected to the flavor eigenstates ν_e, $\nu_\mu$and $\nu_\tau$by a mixing matrix U. The neutrino oscillation probability depends on three mixing angles, $\theta_{12}, \theta_{23}, \theta_{13}$, two mass differences, $\Delta m^2_{12} = m^2_2 - m^2_1$, $\Delta m^2_{23} = m^2_3 - m^2_2$, and a CP phase $\delta_{\rm CP}$. Additional phases are present in the case when neutrinos are Majorana particles, but they do not influence neutrino flavor oscillations at all.

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Three parameters (out of seven) have not yet been measured in neutrino oscillations. The mixing angle θ_{13} is the key parameter of three-neutrino oscillations and regulates at the first order all the oscillation processes that could contribute to the measurement of $\mathrm{sign}(\Delta m^2_{23})$ and δ_{CP}.

θ_{13} searches look for experimental evidence of ν_e appearance in intense accelerator $\nu_\mu$beams in excess of what is expected from the solar terms or in $\overline{\nu}_e$ disappearance detecting the neutrino flux generated by nuclear reactors. The present limit on θ_{13}, mainly driven by the CHOOZ experiment at reactors [2], is $\sin^2\theta_{13} \leq 0.035$ (0.056), 90% C.L. (3σ) [3].

The neutrino mass hierarchy, the order by which mass eigenstates are coupled to flavor eigenstates, can be fixed by measuring the sign of Δm^2_{23}. Its value — $+1$ for the normal hierarchy or -1 for the inverted hierarchy — is of great importance for double-beta decay experiments [4] and it could shed light on possible flavour symmetries.

The CP phase δ_{CP} is the holy grail of ultimate neutrino oscillation searches. The demonstration of CP violation in the lepton sector and the knowledge of the value of this phase would be crucial to understand the origin of the baryon asymmetry in the universe, providing a strong indication, though not proof, that leptogenesis is the explanation for the observed baryon asymmetry of the Universe [5].

All these parameters can be measured via subleading $\nu_\mu \to \nu_e$ oscillations that represent the key process of any future new discovery in neutrino oscillation physics.

1.1. Leptonic CP violation

The phenomenon of CP (or T) violation in neutrino oscillations manifests itself by a difference in the oscillation probabilities of $P(\nu_\mu \to \nu_e)$ *versus* $P(\overline{\nu}_\mu \to \overline{\nu}_e)$(CP violation), or $P(\nu_\mu \to \nu_e)$ *versus* $p(\nu_e \to \nu_\mu)$ (T violation). The CP violation can be seen as interference between the solar and atmospheric oscillation for the same transition. Of experimental interest is the CP-violating asymmetry A_{CP}:

$$A_{\mathrm{CP}} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \tag{1}$$

displayed in Fig. 1 as a function of θ_{13}, or the equivalent time reversal asymmetry A_{T}.

Extensive studies, such as those published in a CERN yellow report [7], the European Network BENE [8] or the International Scoping Study [9] have been already performed to establish the physics potential of future facilities in discovering leptonic CP violation [10].

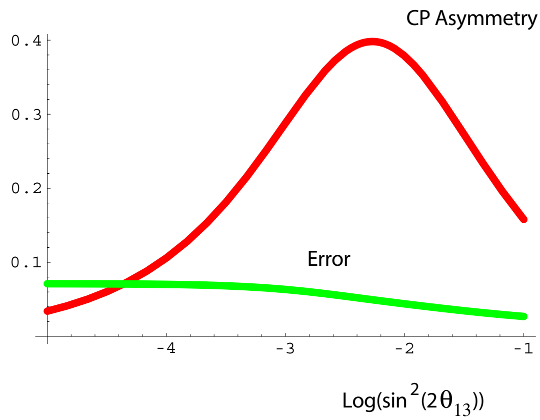

Fig. 1. Magnitude of the CP asymmetry at the first oscillation maximum, for $\delta = 1$ as a function of the mixing angle $\sin^2 2\theta_{13}$. The curve marked "error" indicates the dependence of the statistical+systematic error on such a measurement. The curves have been computed for the baseline beta beam option at the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km, statistical + 2% systematic errors. From [6].

One of the interesting aspects of $\nu_\mu \to \nu_e$ transitions is the occurrence of matter effects which, unlike the straightforward θ_{13} term, depend on the sign of the mass difference sign(Δm^2_{23}). These terms could allow extraction of the mass hierarchy, but could also be seen as a background to the CP violating effect, from which they can be distinguished by the different neutrino energy dependence.

More generally, due to the three-flavor structure of the oscillation probabilities, for a given experimental result several different disconnected regions of the multi-dimensional space of parameters could fit the experimental data, originating degenerate solutions.

Traditionally these degeneracies are referred as the intrinsic or $(\delta_{\rm CP}, \theta_{13})$ degeneracy [11]; the hierarchy or sign(Δm^2_{23})-degeneracy [12]; the octant or θ_{23}-degeneracy [13]. These lead to an eight-fold ambiguity in θ_{13} and $\delta_{\rm CP}$ [14], and hence degeneracies provide a serious limitation for the determination of θ_{13}, $\delta_{\rm CP}$, and sign(Δm^2_{23}).

2. Searches of non vanishing values of θ_{13}

The first objective of the next neutrino oscillation experiments is to look for non-vanishing θ_{13} values. This kind of searches can be performed by accelerator and by reactor experiments and will be briefly discussed in the following. For a comprehensive review of this subject see [15].

Accelerator experiments can measure θ_{13} by detecting the appearance of ν_e neutrinos in accelerator neutrino beams. Neutrino beams are produced through the decay of π and K mesons generated by a high energy proton beam hitting small Z, needle-shaped, segmented targets. Positive (negative) mesons are sign-selected and focused (defocused) by large acceptance magnetic lenses into a long evacuated decay tunnel where ν_μ's ($\overline{\nu}_\mu$'s) are generated.

In case of positive charge selection, the ν_μ beam has typically a few percent of $\overline{\nu}_\mu$ contamination (from the decay of the residual π^-, K^- and K^0) and $\sim 1\%$ of ν_e and $\overline{\nu}_e$ coming from three-body $K^\pm$, K_0 decays and μ decays.

The precision of the evaluation of the intrinsic ν_e to ν_μ contamination is limited by the knowledge of the π and K production in the primary proton beam target requiring a devoted hadroproduction experiment. Recently the Harp experiment [16] measured both the K2K [17] and the MiniBooNE [18] targets, covering most of the useful pion phase-space, successfully improving the description of the two beam lines.

Close detectors are used to directly measure beam neutrinos and backgrounds (for a discussion about close detectors and systematic errors in future LBL experiments see [19]).

The T2K (Tokai to Kamioka) experiment [20] will aim neutrinos from the Tokai site of J-PARC (30 GeV, 0.75 MW) to the Super-Kamiokande detector 295 km away. The neutrino beam is situated at an off-axis angle of 2.5 degrees, ensuring a pion decay peak energy of about 0.6 GeV. The beam line is equipped with a set of dedicated on-axis (INGRID) and off-axis (ND280) near detectors at a distance of 280 m. It is expected that the sensitivity of the experiment in a five-year ν_μ run at the full J-PARC beam intensity, will be of the order of $\sin^2 2\theta_{13} \leq 0.006$ (90% C.L.).

The NOνA experiment, with an upgraded NuMI off-axis neutrino beam [21] ($E_\nu \sim 2$ GeV and a ν_e contamination lower than 0.5%) and a totally active 15 kton liquid scintillator detector at a baseline of 810 km (12 km off-axis), has been approved at FNAL with the aim to explore $\nu_\mu \rightarrow \nu_e$ oscillations with a θ_{13} sensitivity similar to T2K and with some sensitivity to $\mathrm{sign}(\Delta m^2_{23})$ thanks to the relatively long baseline.

Another approach to searching for non-vanishing θ_{13} is to look at $\overline{\nu}_e$ disappearance using nuclear reactors as neutrino sources. In $\overline{\nu}_e$ disappearance experiments θ_{13} is directly linked to the detected oscillation signal without any interference from δ_{CP} and $\mathrm{sign}(\Delta m^2_{23})$. Their result is truly complementary to the accelerators. On the other hand reactor experiments cannot have any role in direct searches for leptonic CP violation or mass hierarchy determination.

The Double Chooz [22] experiment in France will employ a far detector in the same location as the former CHOOZ detector as well as a near detector. The sensitivity after five years of data taking will be $\sin^2 2\theta_{13} = 0.025$ at 90% C.L. The Daya Bay project in China [23] could reach a $\sin^2 2\theta_{13}$ sensitivity below 0.01, while the RENO experiment in Korea [24] should reach a sensitivity around 0.02.

A sketch of θ_{13} discovery potential of future experiments as a function of the time is reported in Fig. 2 [15].

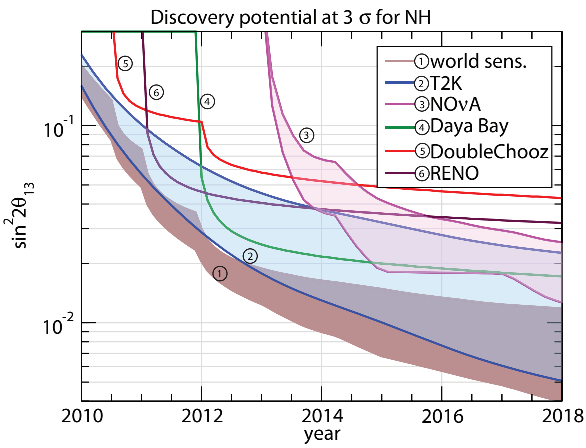

Fig. 2. Evolution of the θ_{13} discovery potential as a function of time (3σ C.L.) for NH, showing the global sensitivity reach. The bands for the beams and the global reach reflect the (unknown) true value of δ. From [15].

3. A new generation of facilities for the physics of neutrino oscillations

A global fit of T2K plus NOνA plus reactors will not be able to provide firm results (3σ or better) about leptonic CP violation [25] or sign(Δm^2_{23}) [25, 26] whatever the value of θ_{13}.

A further generation of long-baseline neutrino experiments will be needed to address this very important search in physics. As a rule of thumb they should be at least one order of magnitude more sensitive than T2K or NOνA a condition equivalent to an increase of two orders of magnitude on neutrino statistics, with a consequent important reduction of systematic errors.

Proposal for this very challenging task are base either on conventional neutrino beams pushed to their ultimate power, Section 3.1 or to innovative concepts about neutrino production, Section 3.2.

3.1. Neutrino super beams

To fulfill the needs of searches for leptonic CP violation, conventional neutrino beams must be pushed to their ultimate limits (neutrino super beams) [27] and gigantic (megaton scale) neutrino detectors must be built.

Phase II of the T2K experiment, often called T2HK [28], foresees an increase of beam power up to the maximum feasible with the accelerator and target (4 MW beam power), antineutrino runs, and a very large, 520 kt, water Čerenkov detector, Hyper-Kamiokande or HK, to be built close to Super-Kamiokande. An evolution of T2HK is the T2KK [29, 30] project, where half of the HK detector would be installed in Japan, while the second half would be mounted in Korea, at a baseline of about 900 km, around the second oscillation maximum. The case of intermediate baselines and liquid argon detectors has also been studied [31].

A wide-band beam (WBB) has been proposed at Fermilab upgrading the FNAL main injector after the end of the Tevatron programme [32]. A conventional wide-band neutrino would be sent to a 300 kton water Čerenkov detector ($3 \div 6$ liquid argon modules of 20 kton are also taken in consideration) at the Homestake mine, at a baseline of 1290 km. Wide-band beams possess the advantages of a higher on-axis flux and a broad energy spectrum. The latter allows the first and second oscillation nodes in the disappearance channel to be observed, providing a strong tool to solve the degeneracy problem [33]. On the other hand, experiments served by wide-band beams must determine the incident neutrino energy with good resolution and eliminate the background from the high energy tail of the spectrum. The very long-baseline decreases the event rate at the far detector (neutrino flux at the second oscillation maximum is reduced by a factor nine only partially recovered by the higher neutrino cross-section) in an experiment where the statistics is very important and reduces the sensitivity of the experiment to θ_{13} and CP-violation.

In Europe, the perspectives for a high intensity neutrino experiment based on super beams are entangled with the evolution of the CERN acceleration complex and, in particular, of the injection system of the LHC. In these directions super beams based on upgrades of the CNGS, Section 3.1.1, on a high power SPL, Section 3.1.2, or on a high power PS2, Section 3.1.3 have been studied. For a recent review of the subject see also [34].

3.1.1. CNGS upgrades

The CNGS at nominal intensity can be operated to accumulate 4.5×10^{19} protons on target (p.o.t.)/y at an energy of 400 GeV. In the last few years, particularly in the framework of the CERN PAF (Proton Accelerators for

Future) Working Group, it has been investigated [35] the possibility of increasing the intensity of the CNGS both using present facilities and, on a longer timescale, exploiting an upgrade of the acceleration complex.

The ultimate CNGS performance are actually limited by the injection from the 50-year-old Proton Synchrotron (PS). In this scenario (CNGS as the only user of the SPS at CERN beyond the LHC), the facility could deliver up to 1×10^{20} p.o.t./y. At a longer timescale, the replacement of the PS with a new 50 GeV synchrotron (PS2) might surpass these limitations, provided an appropriate upgrade of the SPS radio-frequency system.

It would bring CNGS to a maximum intensity (CNGS as only user of the SPS beyond the LHC) of 2×10^{20} p.o.t./y.

Studies about performances of CNGS upgrades with a new setup firing a lower energy neutrino beam off-axis to a 100 kton [36] or 20 kton [37] liquid argon detector near the LNGS, show anyway that only a proton intensity one order of magnitude higher than the present CNGS intensity could allow a sensitive search for leptonic CP violation. This would require a complete refurbishment of the SPS accelerator on top of the above mentioned upgrades of the injection scheme.

3.1.2. CERN-SPL

In the CERN-SPL super beam project (SPL-SB) [38, 39] the planned 4MW SPL (Superconducting Proton Linac) would deliver a 3.5 GeV/c H^- beam on a mercury (or carbon) target to generate a neutrino beam with an average energy of ~ 0.3 GeV [1].

The ν_e contamination from K will be suppressed by threshold effects and the resulting ν_e/ν_μ ratio ($\sim 0.4\%$) will be known within 2% error. The use of a near and far detector (the latter at $L = 130$ km in the Fréjus area) will allow for both ν_μ-disappearance and $\nu_\mu \to \nu_e$ appearance studies. The physics potential of the SPL super beam (SPL-SB) with a water Čerenkov far detector with a fiducial mass of 440 kt, MEMPHYS, has been extensively studied [41,42]. The most updated sensitivity estimations for this setup have been published in Ref. [43].

The MEMPHYS (Megaton Mass Physics) detector [44] is a megaton-class water Čerenkov designed to be located at Fréjus, 130 km from CERN, addressing both the non-accelerator domain (nucleon decay, SuperNovae neutrino from burst event or from relic explosion, solar and atmospheric neutrinos) and the accelerator (super beam, beta beam) domain [45].

[1] At present SPL is foreseen as one of the elements of a new injection chain for the SPS, in view of the LHC luminosity upgrades [40]. In this context a power of 0.4 MW would be enough. Extensions to 4 MW could be driven by the needs of a neutrino super beam or a proton driver for a neutrino factory and/or a proton driver for EURISOL.

3.1.3. CERN-PS2

It has been proposed in [46] to generate a neutrino beam by a high power, 1.6 MW, version of the PS2 accelerator, a 50 GeV synchrotron designed to run at 0.4 MW to serve as a component of the new injection scheme for the LHC. Neutrinos could be then fired to a 100 kton liquid argon detector, placed at a distance of 950 km or 1544 km or 2300 km. The distances correspond to the three underground labs of Sieroszowice in Poland, Slanic in Romania and Pyhasalmi in Finland respectively, three candidates actually taken in consideration by the Laguna [47] FP7 Design Study.

As in the case of the WBB at Dusel, this setup would measure neutrinos at the first and at the second oscillation maximum. Liquid argon is certainly the best candidate to fulfill the requirements of this configuration. And following the discussion about the WBB, this kind of configuration would have excellent performances in measuring sign(Δm^2_{23}) but a limited sensitivity for leptonic CP violation and the measurement of θ_{13}.

3.2. New concepts on neutrino beams

The super beam approach can be quite powerful if θ_{13} happens to be sufficiently large, in the range of values will be explored by the T2K, NOνA and the reactor experiments. For smaller values it shows evident limitations:

- It is not a "pure" source of neutrinos of a given flavor, being contaminated by the ν_e produced by the decay-in-flight of the kaons and of the muons. When seeking for sub-dominant $\nu_\mu \to \nu_e$ transitions, the systematics on the knowledge of the ν_e contamination will likely be the main limitation for a precise determination of CP violation in the leptonic sector [19].
- The ultimate precision with which the neutrino flux can be predicted is limited by the precision of the hadroproduction cross-sections of the neutrino parents, that are secondary particles generated in a primary proton beam.
- The suppression of the antineutrino interaction rate due to the cross-section ($\sigma_{\bar{\nu}}/\sigma_\nu \simeq 1/2$), makes the antineutrino run much more time-consuming that the neutrino run, with a higher contamination of opposite helicity neutrinos.

The intrinsic limitations of conventional neutrino beams can be overcome if the neutrino parents are fully selected, collimated and accelerated to a given energy. This can be attempted within the muon lifetime, bringing to the neutrino factory [48], or within beta decaying ion lifetimes, bringing to the beta beam [49, 50].

With this challenging approach several important improvements can be made to conventional neutrino beams:

- The neutrino fluxes would be simply derived from the knowledge of the number of parents circulating in the decay ring and from their Lorentz boost factor γ.
- The energy shape of the neutrino beam would be defined by just two parameters, the end-point energy Q_β of the beta decaying parent and its Lorentz boost factor γ.
- The intrinsic neutrino backgrounds would be suppressed (in the case of beta beam) or reduced to wrong sign muons (golden channel in neutrino factories).

The technological problems derive from the fact that the parents need to be unstable particles, requiring a fast, efficient acceleration scheme.

3.3. Neutrino factories

Production, acceleration and stacking of high intensity muon beams for muon colliders have been envisaged since the 60's; their decays might produce useful beams of ν_μ and $\overline{\nu}_e$ (exploiting μ^- decays into $e^-\overline{\nu}_e\nu_\mu$) or $\overline{\nu}_\mu$ and ν_e (μ^+ decays into $e^+\nu_e\overline{\nu}_\mu$).

In the modern formulation of the "Neutrino Factory" (NF) concept [48], muons are created from an intense pion source at low energies, their phase space compressed to produce a bright beam, which is then accelerated to the desired energy and injected into a storage ring with long straight sections pointing in the desired direction. The neutrino factory design can be considered a strong physics-motivated intermediate step towards a Muon Collider.

It is possible to investigate $\nu_e \to \nu_\mu$ oscillations seeking for the appearance of μ^- from ν_μ CC events ("wrong sign muons"), provided that they can be separated from the bulk of μ^+ ("right sign muons") coming from unoscillated $\overline{\nu}_\mu$. A suitable detector to search for these transitions is an iron magnetized detector [51].

As firstly underlined in [52], the simultaneous exploitation of μ^- and μ^+ decays would be an ideal tool to address CP violation in the leptonic sector, with outstanding performances compared with pion-based sources.

The realization of the neutrino factory still represents a major accelerator challenge compared with neutrino super beams. It is met through a world-wide R&D programme; in Europe this programme is especially fostered by UK. Among the NF-oriented projects we recall MICE at the Rutherford Appleton Laboratories (ionization cooling), HARP at CERN (hadroproduction for the front-end proton accelerator), MERIT at CERN (targetry), EMMA at Daresbury (fixed-field alternating-gradient accelerators) and the MUCOOL R&D at Fermilab (radio-frequency and absorbers). Moreover, the NF has to be seeded by a very powerful low-energy proton accelerator (4–12 MW); its realization requires similar R&D as for the super beams, although its optimal energy lays in the few-GeV range (*e.g.* the aforementioned SPL). Current designs aim at 10^{21} muon decays per year running with a muon energy of 20 GeV.

After the work of the International Scoping Study (ISS) [9, 53, 54], there is a rather widespread consensus on the fact that the Neutrino Factory can be considered the ultimate facility for the determination of θ_{13}, CP violation and the mass hierarchy. With respect to super beams, they profit of much smaller systematics in the knowledge of the source and much higher energies (*i.e.* statistics, due to the linear rise of the deep-inelastic ν_μ cross-section with energy). In fact, the energy is so high that for any realistic baseline (< 7000 km) the ratio L/E will be off the peak of the oscillation maximum at the atmospheric scale. This condition is the main cause of the occurrence of multiple solutions when the mixing parameters are extracted from the physics observables, *i.e.* the rates of appearance of wrong sign muons, see the discussion of Section 1.1. It also affects other facilities than NF but it is particularly severe for experiments running off the peak of the oscillation probability. The ISS suggests as an ideal solution the positioning of two detectors at baseline around 3000 and 7000 km.

An alternative to the second 7000 km detector could be the detection of $\nu_e \to \nu_\tau$ transitions at baseline around 1000 km ("silver channel") [55]). The exploitation of the silver channel, moreover, is useful to investigate the occurrence of non-standard interactions in the neutrino sector [56].

Although the superior physics reach of the Neutrino Factory is nearly undisputed and no evident showstoppers have been identified, the R&D needed to build this facility remains impressive. In turn it becomes urgent to fairly define the time schedule for its realization and the cost estimate as in the tasks of the EuroNu FP7 Design Study [57].

3.4. Beta beams

The enormous progress in the technology of Radioactive Ion Beams has led Zucchelli [49] to the proposal of a neutrino facility based on the decay in flight of β-unstable ions (for a full review see [50]). Unlike the NF, these beta beams (BB) are pure sources of $\overline{\nu}_e$, or, in the occurrence of β^+ decays, of ν_e. Hence, they are ideal tools to study $\nu_e \to \nu_\mu$ transitions and their CP-conjugate. They share with NF the nearly complete absence of systematics in the knowledge of the source with the bonus of no "right sign muon" background (no ν_μ in the initial state). On the other hand, due to the very different mass-to-charge ratio between muons and β-unstable ions, the energy of the neutrinos are typically much smaller than what can be obtained at the NF, and the decay ring where the ions are stored to decay needs to be much longer (about 7 km) because of the much higher magnetic rigidity of the ions with respect to the muons.

The original proposal of [49] was tuned to leverage at most the present facilities of CERN — the PS and the SPS — and it was based on ^{6}He and ^{18}Ne as $\overline{\nu}_e$ and ν_e sources respectively. It goes without saying that the beta beam triggered the interest of nuclear physics community, which was offered a stimulating synergy with the neutrino programme at CERN. As a result, such proposal [44, 58] was studied in a systematic manner within the framework of the EURISOL FP6 Design Study [59]. The study aimed at 2.9×10^{18} antineutrinos per year from ^{6}He and 1.1×10^{18} neutrinos per year from ^{18}Ne.

The outcome had been extremely encouraging, except for the production of ^{18}Ne, which cannot attain the needed rate using standard methods and medium-intensity proton accelerators (200 kW). Ways to improve the ^{18}Neyield are among the tasks of EuroNu, a viable alternative appears to be the direct production on MgO based on a 2 MW, few MeV, proton accelerators. In this case, the BB would partially miss the advantage of a low-power front-end compared with the multi-MW accelerators needed for the super beams and for the NF, although a few tens of MeV MW accelerator is anyway a much simpler machine than a few GeV MW Linac.

As in the case of the SPL-SB the Eurisol Beta Beam would detect neutrino oscillation on the peak of the first oscillation maximum at a baseline that guarantees the absence of matter effects that are a source of not genuine CP violating oscillations. As discussed in [43] sensitivity on $\mathrm{sign}(\Delta m^2_{23})$ would be partially recovered by the synergetic combination of beam neutrinos with atmospheric neutrinos detected by MEMPHYS. On the other hand the sub-GeV energy range of the Eurisol beta beam neutrinos reflects in depleted neutrino cross-sections, impacting on the overall performances of the setup.

A very interesting experimental possibility is that neutrinos created by the SPL could be fired to the same detector of the Eurisol beta beam [60].

The beta beam and the SPL-SB could share the same injector, the SPL, since radioactive ion production requires about 0.2 MW while the SPL could deliver up to 4 MW of power. Furthermore the two neutrino beam would have similar energies and so they could share the same far detector.

The combination of a super beam with a beta beam in the same experiment can provide an experimental environment with very unique characteristics: The two beams can be used to separately study CP channels like $\nu_\mu \to \nu_e$ *versus* $\overline{\nu}_\mu \to \overline{\nu}_e$ and $\nu_e \to \nu_\mu$ *versus* $\overline{\nu}_e \to \overline{\nu}_\mu$; T transitions like $\nu_\mu \to \nu_e$ *versus* $\nu_e \to \nu_\mu$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ *versus* $\overline{\nu}_e \to \overline{\nu}_\mu$ and also CPT transitions like $\nu_\mu \to \nu_e$ *versus* $\overline{\nu}_e \to \overline{\nu}_\mu$ and $\nu_e \to \nu_\mu$ *versus* $\overline{\nu}_\mu \to \overline{\nu}_e$.

The addition of a super beam to a beta beam could also complement some of the weak points of the beta beam, namely the lack of sensitivity to the atmospheric parameters θ_{23} and Δm^2_{23} and the lack of ν_μ events in the close detector, useful for calibrating beta beam signal efficiency and measuring the ν_e/ν_μcross-section ratio.

Performances of the SPL-SB, the Eurisol beta beam and their combination are displayed in Fig. 3.

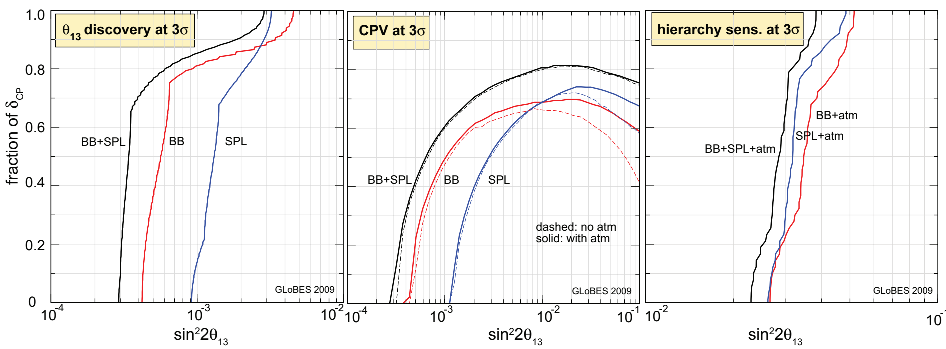

Fig. 3. 3σ sensitivities for the beta beam, the SPL super beam and their combination, including or not the atmospheric neutrino data (solid and dashed lines respectively). Computed as a function of the fraction of all possible values of $\delta_{\rm CP}$. Left panel: sensitivity to θ_{13}, central panel: sensitivity to leptonic CP violation, right panel: sensitivity to the mass hierarchy, adapted from [43] (courtesy of T. Schwetz).

To improve the performances of the beta beam several alternatives to the SPS have been considered: a refurbished 1 TeV SPS ("SuperSPS" [40]) envisaged for the energy and luminosity upgrade of the LHC or even the LHC itself [61,62], an option that nowadays seems far in the future if not unlikely. These configurations improve the sensitivities to CP violation and the mass hierarchy at the expense of a large increase of costs: large investments are needed especially to the construction of the decay ring since the length of the ring depends from the magnetic rigidity of the circulating ions, which is proportional to their Lorentz γ factor.

In 2006, C. Rubbia *et al.* [63] proposed the use of ^{8}Li and ^{8}B as neutrino sources noting that these isotopes could be produced in a multiturn passage of a low-energy ion beam through a low-Z target. In this case, ionization cooling techniques could increase the circulating beam lifetime and thus enhance the ion production to a level suitable for the beta beam. This option has the advantage of employing isotopes with higher Q-value than ^{18}Ne and ^{6}He, increasing correspondingly the neutrino energy (from ~ 0.5 to ~ 1.5 GeV for the SPS-based BB). This alternative approach will be at focus in the framework of the EUROν FP7 Design Study [57].

It follows from the beta beam merit factor $\mathcal{M}$ [50]

$$\mathcal{M} \propto \frac{\gamma}{Q_\beta} \tag{2}$$

that performances are inversely proportional to the endpoint energy Q_β. For this reason for the same baseline an high-Q BB needs an order of magnitude more ions at the source to match the performances of a high-γ BB, [64].

A further option for beta beams is the possibility of creating monochromatic neutrino beams [65] based on electron capture processes of radioactive ions, rather than on their beta decays. The main limitations of these appealing setups are the technical difficulties of the production and acceleration schemes.

Concluding, beta beam performance are in between the performances of super beams and neutrino factory. The clarification of the issue of the ion production yield is considered a crucial milestone for the beta beam. Given an appropriate yield, the acceleration and stacking is viewed as less demanding than what is needed for a NF both from the point of view of R&D and cost. Clearly, the possibility of employing existing facilities (*e.g.* the CERN PS-SPS complex or its upgrades) might substantially strengthen this option.

4. Conclusions

Several different options have already been put forward to address the challenging experimental needs of future experiments looking to leptonic CP violation.

They can exploit conventional neutrino beams pushed to their ultimate performances, neutrino super beams, or innovative concepts about neutrino beam production like the neutrino factories and the beta beams.

A comparison of the sensitivities of the different facilities, as that produced by the ISS [9] and reported in Fig. 4, shows that leptonic CP violation can be discovered provided that $\sin^2 2\theta_{13}$ is not four order of magnitudes below the present experimental limit.

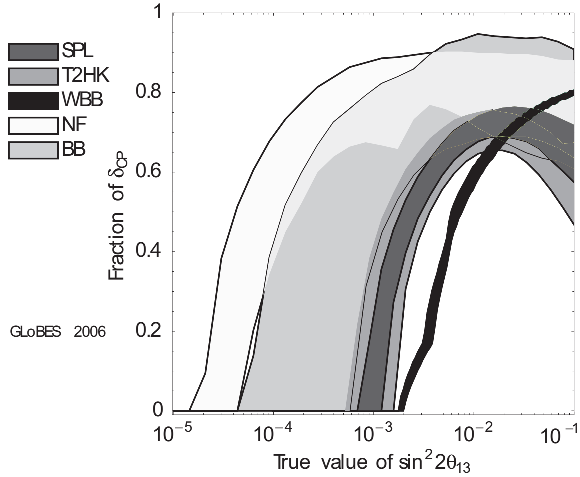

Fig. 4. The discovery reach at 3 σ level for different facilities in leptonic CP violation sensitivity. The discovery limits are shown as a function of the fraction of all possible values of the true value of the CP phase δ ('Fraction of $\delta_{\rm CP}$') and the true value of $\sin^2 2\theta_{13}$. The right-hand edges of the bands correspond to the conservative setups while the left-hand edges correspond to the optimized setups. The discovery reach of the SPL super beam is shown as the orange band, that of T2HK as the yellow band, and that of the wide-band beam experiment as the green band. The discovery reach of the beta beam is shown as the light green band and the neutrino factory discovery reach is shown as the blue band. From reference [9].

Ultimate performances can be reached by the neutrino factory. However if θ_{13} happens to be on the reach of the next generation experiments, $\sin^2 2\theta_{13} \geq 0.01$, super beams and beta beams could be very competitive being less demanding on R&D developments and costs. For this reason a firm assessment about the costs and the timescales of the different facilities, as the ongoing effort within the EuroNu Design Study, will be an important milestone to define a global strategy for these developments.

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REFERENCES

[1] Y. Fukuda *et al.* [Super-Kamiokande], *Phys. Rev. Lett.* **81**, 1562 (1998).

[2] M. Apollonio *et al.* [CHOOZ], *Eur. Phys. J.* **C27**, 331 (2003).

[3] T. Schwetz, M. Tortola, J.W.F. Valle, *New J. Phys.* **10**, 113011 (2008).

[4] F. Feruglio, A. Strumia, F. Visani, *Nucl. Phys.* **B637**, 345 (2002).

[5] M. Fukugita, T. Yanagida, *Phys. Lett.* **B174**, 45 (1986).

[6] A. Blondel *et al.*, *Acta Phys. Pol. B* **37**, 2077 (2006).

[7] M. Apollonio *et al.* [CERN Working Group on Oscillation Physics at the Neutrino Factory], `hep-ph/0210192` 2002.

[8] A. Baldini *et al.* [BENE Steering Group], CERN-2006-005.

[9] A. Bandyopadhyay *et al.* [ISS Physics Working Group], *Rep. Prog. Phys.* **72**, 106201 (2009).

[10] A. Guglielmi, M. Mezzetto, P. Migliozzi, F. Terranova, `hep-ph/0508034`, published in D. Bettoni *et al.*, *Phys. Rep.* **434**, 47 (2005).

[11] J. Burguet-Castell, M.B. Gavela, J. Gomez-Cadenas, P. Hernandez, O. Mena, *Nucl. Phys.* **B608**, 301 (2001).

[12] H. Minakata H. Nunokawa, *J. High Energy Phys.* **10**, 001 (2001).

[13] G.L. Fogli E. Lisi, *Phys. Rev.* **D54**, 3667 (1996).

[14] V. Barger, D. Marfatia, K. Whisnant, *Phys. Rev.* **D65**, 073023 (2002).

[15] M. Mezzetto T. Schwetz, `arXiv:1003.5800[hep-ph]`.

[16] M.G. Catanesi *et al.* [HARP], *Nucl. Instrum. Methods* **A571**, 527 (2007).

[17] M.G. Catanesi *et al.* [HARP], *Nucl. Phys.* **B732**, 1 (2006).

[18] M.G. Catanesi *et al.* [HARP], *Eur. Phys. J.* **C52**, 29 (2007).

[19] P. Huber, M. Mezzetto, T. Schwetz, *J. High Energy Phys.* **03**, 021 (2008).

[20] Y. Itow *et al.* [T2K], `hep-ex/0106019`.

[21] I. Ambats *et al.* [NOvA], `hep-ex/0503053`.

[22] F. Ardellier *et al.* [Double Chooz], `hep-ex/0606025`.

[23] X. Guo *et al.* [Daya-Bay], `hep-ex/0701029`.

[24] J.K. Ahn *et al.* [RENO], `arXiv:1003.1391[hep-ex]`.

[25] P. Huber, M. Lindner, T. Schwetz, W. Winter, *J. High Energy Phys.* **11**, 044 (2009).

[26] O. Mena, H. Nunokawa, S.J. Parke, *Phys. Rev.* **D75**, 033002 (2007).

[27] B. Richter, `hep-ph/0008222`.

[28] T. Kobayashi, *J. Phys. G* **29**, 1493 (2003).

[29] M. Ishitsuka, T. Kajita, H. Minakata, H. Nunokawa, *Phys. Rev.* **D72**, 033003 (2005).

[30] T. Kajita, S.B. Kim, A. Rubbia, `arXiv:0808.0650[hep-ph]`.

[31] A. Badertscher *et al.*, `arXiv:0804.2111[hep-ph]`.

[32] M. Diwan *et al.*, `arXiv:hep-ex/0608023`.

[33] M.V. Diwan, *Int. J. Mod. Phys.* **A18**, 4039 (2003).

[34] R. Battiston, M. Mezzetto, P. Migliozzi, F. Terranova, `0912.3372[hep-ex]`.

[35] M. Meddahi E. Shaposhnikova, CERN-AB-2007-013, 2007.

[36] A. Meregaglia A. Rubbia, *J. High Energy Phys.* **11**, 032 (2006).

[37] B. Baibussinov *et al.*, *Astropart. Phys.* **29**, 174 (2008).

[38] B. Autin *et al.*, CERN-2000-012.

[39] R. Garoby, *AIP Conf. Proc.* **773**, 239 (2005).

[40] O. Bruning *et al.*, CERN-LHC-PROJECT-REPORT-626;.

[41] J.J. Gomez-Cadenas *et al.*, `hep-ph/0105297`.

[42] M. Mezzetto, *J. Phys. G* **29**, 1781 (2003).

[43] J.-E. Campagne, M. Maltoni, M. Mezzetto, T. Schwetz, *J. High Energy Phys.* **04**, 003 (2007).

[44] A. de Bellefon *et al.*, `hep-ex/0607026`.

[45] D. Autiero *et al.*, *J. Cosm. Astropart. Phys.* **0711**, 011 (2007).

[46] A. Rubbia, `arXiv:1003.1921[hep-ph]`.

[47] `http://www.laguna-science.eu/`

[48] S. Geer, *Phys. Rev.* **D57**, 6989 (1998).

[49] P. Zucchelli, *Phys. Lett.* **B532**, 166 (2002).

[50] M. Lindroos, M. Mezzetto, *Beta Beams: Neutrino Beams*, UK: Imperial College Pr., London, 2009, p.154.

[51] A. Cervera, F. Dydak, J. Gomez Cadenas, *Nucl. Instrum. Methods* **A451**, 123 (2000).

[52] A. De Rujula, M.B. Gavela, P. Hernandez, *Nucl. Phys.* **B547**, 21 (1999).

[53] J.S. Berg *et al.* [ISS Accelerator Working Group], *JINST* **4**, P07001 (2009).

[54] T. Abe *et al.* [ISS Detector Working Group], *JINST* **4**, T05001 (2009).

[55] A. Donini, D. Meloni, P. Migliozzi, *Nucl. Phys.* **B646**, 321 (2002).

[56] J. Kopp, T. Ota, W. Winter, *Phys. Rev.* **D78**, 053007 (2008).

[57] `http://www.euronu.org`

[58] J. Bouchez, M. Lindroos, M. Mezzetto, *AIP Conf. Proc.* **721**, 37 (2004).

[59] `http://www.eurisol.org`

[60] M. Mezzetto, *Nucl. Phys. Proc. Suppl.* **149**, 179 (2005).

[61] J. Burguet-Castell *et al.*, *Nucl. Phys.* **B695**, 217 (2004).

[62] A. Donini *et al.*, *Eur. Phys. J.* **C48**, 787 (2006).

[63] C. Rubbia, A. Ferrari, Y. Kadi, V. Vlachoudis, *Nucl. Instrum. Methods* **A568**, 475 (2006).

[64] E. Fernandez-Martinez, *Nucl. Phys.* **B833**, 96 (2010).

[65] J. Bernabeu, J. Burguet-Castell, C. Espinoza, M. Lindroos, *J. High Energy Phys.* **12**, 014 (2005).