Search for CP and CPT violation effects in neutrino oscillations

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Abstract. The present generation of long baseline neutrino experiments, both at accelerators and at reactors, is looking (or it’s just going to look) for oscillation signals generated by the mixing parameter $\theta_{13}$. The knowledge of this angle is a fundamental milestone to optimize further experiments aimed at detecting CP violation in the neutrino sector. Leptonic CP violation is a key phenomenon that has profound implications in particle physics and cosmology but it is clearly out of reach for the aforementioned experiments. Since late 90’s, 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 counterpart of the Cabibbo-Kobayashi-Maskawa matrix. The experimental status of searches or hints for CPT violation in the neutrino sector will be briefly summarized too.

1. Neutrino Oscillations
Neutrino oscillation experiments had been very successful in the past 15 years. Neutrino oscillations had been discovered in 1998 by the Super Kamiokande experiment [1] by analyzing atmospheric neutrinos. The measurement was confirmed by Macro[2] and Soudan II[3]. The same oscillations had been then measured by exploiting artificial neutrino beams by the K2K [3] and MINOS [4] experiments. In 2002 the SNO experiment [5] settled the solar neutrino puzzle by demonstrating, in a model independent way, that it was generated by neutrino oscillations, concluding a long standing experimental saga initiated by Ray Davis in the late sixties[6] and continued by Kamiokande[7], SuperKamiokande[8] and the two gallium experiments Gallex-GNO[9, 10] and Sage[11, 12]. Soon after SNO, the KamLAND [13] experiment detected the same kind of oscillation acting on reactor antineutrinos.

The discovery of neutrino oscillations establishes 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 $\nu_1, \nu_2, \nu_3$ with mass values $m_1, m_2$ and $m_3$ that are connected to the flavor eigenstates $\nu_e$, $\nu_\mu$, 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, $\Delta m^2_{12} = m_2^2 - m_1^2$, $\Delta m^2_{23} = m_3^2 - m_2^2$, and a CP phase $\delta_{CP}$. Additional phases are present in case neutrinos are Majorana particles, but they do not influence neutrino flavor oscillations at all.

The best-fit values and allowed range of values of the oscillation parameters are shown in Table 1.
Table 1. Best-fit values, 2σ, and 3σ intervals (1 dof) for the three flavor neutrino oscillation parameters from global data including solar, atmospheric, reactor and accelerator experiments [14].

| parameter                      | best fit       | 2σ            | 3σ            |
|--------------------------------|---------------|---------------|---------------|
| $\Delta m_{21}^2$ [$10^{-5}eV^2$] | $7.59^{+0.23}_{-0.18}$ | $7.22$--$8.03$ | $7.03$--$8.27$ |
| $|\Delta m_{31}^2|$ [$10^{-3}eV^2$] | $2.40^{+0.12}_{-0.11}$ | $2.18$--$2.64$ | $2.07$--$2.75$ |
| $\sin^2 \theta_{12}$              | $0.318^{+0.019}_{-0.016}$ | $0.29$--$0.36$ | $0.27$--$0.38$ |
| $\sin^2 \theta_{23}$              | $0.50^{+0.07}_{-0.06}$ | $0.39$--$0.63$ | $0.36$--$0.67$ |
| $\sin^2 \theta_{13}$              | $0.013^{+0.013}_{-0.009}$ | $\leq 0.039$ | $\leq 0.053$ |

The results from the LSND experiment [15], reporting a 3.6σ evidence of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with a third, very distinct, neutrino mass difference: $\Delta m_{LSND}^2 \sim 0.3$ -- $6$ eV$^2$, cannot be accommodated in a three neutrino scheme. They have been recently confirmed by the MiniBooNE collaboration [16] (the same collaboration did not detect any $\nu_\mu \rightarrow \nu_e$ transition [17]). To explain the whole set of data at least four different light neutrino species would have been needed (referred as “3+1” models, where the first three are active neutrinos and the fourth is a sterile neutrino). These 3 + 1 models provided anyway poor overall fits to the existing global experimental data [18]. Very recently an updated full computation of the antineutrino fluxes from reactors [19] suggested that the past short baseline experiments at reactors should be interpreted as an evidence of $\bar{\nu}_e$ disappearance [20]. As a consequence the latest fits to the global neutrino data prefer a “3+2” neutrino scheme over the conventional models with three neutrinos [21].

Three parameters (out of seven) have not yet been measured in neutrino oscillations.

The mixing angle $\theta_{13}$ 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 mass hierarchy and leptonic CP violation.

The neutrino mass hierarchy, the order by which mass eigenstates are coupled to flavor eigenstates, can be fixed by measuring the sign of $\Delta m_{31}^2$. Its value could be $+1$ (normal hierarchy), in which case $\nu_e$ would be the lightest neutrino, or $-1$ (inverted hierarchy), for which $\nu_e$ would be the heaviest. Its value is of great importance for double-beta decay experiments [22] and it could shed light on possible flavour symmetries.

The CP phase $\delta_{CP}$ is the ultimate goal of 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 [23].

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

1.1. Sub Leading $\nu_\mu \rightarrow \nu_e$ oscillations
The $\nu_\mu \rightarrow \nu_e$ transition probability can be parametrized in different ways, see for instance [24],[25], where terms driven by $\theta_{13}$ appear together with CP-even and CP-odd terms, terms driven by the solar parameters and matter effects. A sketch of $P(\nu_\mu \rightarrow \nu_e)$ as a function of the baseline $L$ for 1 GeV neutrinos is shown in Fig. 1.
1.2. Leptonic CP violation

The ultimate challenge of oscillation neutrino physics will be to determine whether CP is violated or not in neutrino oscillations. The experimental information relies on the fact that some terms of $P(\nu_\mu \rightarrow \nu_e)$ change sign by exchanging neutrinos with antineutrinos (i.e. the CP-odd term in Fig 1). In this way the probability of oscillation for neutrino will result different from the probability of antineutrinos. This allows to build a CP-violating asymmetry $A_{CP}$:

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$  (1)

displayed in Figure 2 as a function of $\theta_{13}$, or the equivalent time reversal asymmetry $A_T$.

The richness of the $\nu_\mu \rightarrow \nu_e$ transition is also its weakness: it will be difficult to extract all the genuine parameters unambiguously. 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 to as the intrinsic or $(\delta_{CP}, \theta_{13})$ degeneracy [25]; the hierarchy or $\text{sign}(\Delta m^2_{23})$-degeneracy [28]; the octant or $\theta_{23}$-degeneracy [29]. These lead to an eight-fold ambiguity in $\theta_{13}$ and $\delta_{CP}$ [30], and hence degeneracies provide a serious limitation for the determination of $\theta_{13}$, $\delta_{CP}$, and $\text{sign}(\Delta m^2_{23})$.

2. Searches of non vanishing values of $\theta_{13}$

The first objective of neutrino oscillation experiments is to look for non-vanishing $\theta_{13}$ 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 [31, 32].

Accelerator experiments can measure $\theta_{13}$ by detecting the appearance of $\nu_e$ neutrinos in accelerator neutrino beams.

Neutrino beams are produced by the decay of $\pi$ and K mesons generated by a high energy proton beam hitting small Z, needle-shaped, segmented targets, see Fig. 3. Positive (negative)
Figure 2. 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 [27].

mesons are sign-selected and focused (defocused) by large acceptance magnetic lenses into a long evacuated decay tunnel where $\nu_\mu$’s ($\overline{\nu}_\mu$’s) are generated. In case of positive charge selection, the $\nu_\mu$ beam has typically a few percent of $\overline{\nu}_\mu$ contamination (from the decay of the residual $\pi^-, K^-$ and $K^0$) and $\sim$ 1% of $\nu_e$ and $\overline{\nu}_e$ coming from three-body $K^\pm, K_0$ decays and $\mu$ decays.

The precision of the evaluation of the intrinsic $\nu_e$ to $\nu_\mu$ contamination is limited by the knowledge of the $\pi$ and $K$ production in the primary proton beam target requiring a devoted hadroproduction experiment. Recently the Harp experiment [33] measured both the K2K [34] and the MiniBooNE [35] 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 [36]).

The T2K (Tokai to Kamioka) experiment [37] is aiming neutrinos from the Tokai site of J-PARC (30 GeV, 0.75 MW) to the Super-Kamiokande detector 295 km away, at an off-axis angle of 2.5 degrees from the neutrino beam, ensuring a neutrino 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 $\nu_\mu$ run at the full J-PARC beam intensity, will be of the order of $\sin^2 2\theta_{13} \leq 0.006$ (90% CL). The experiment started data taking at the beginning of 2010 and already released
The NOνA experiment with an upgraded NuMI off-axis neutrino beam [39] ($E_\nu \sim 2$ GeV and a $\nu_e$ contamination lower than 0.5%), a totally active 15 kton liquid scintillator detector and with 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 $\theta_{13}$ sensitivity similar to T2K and with some sensitivity to $\text{sign}(\Delta m_{23}^2)\text{ thanks to the longer baseline.}$

Another approach to searching for non-vanishing $\theta_{13}$ is to look at $\nu_e$ disappearance using nuclear reactors as neutrino sources. In $\nu_e$ disappearance experiments $\theta_{13}$ is directly linked to the detected oscillation signal without any interference from $\delta_{CP}$ and $\text{sign}(\Delta m_{23}^2)$. 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.

The Double Chooz [40] 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% CL. The Daya Bay project in China [41] could reach a $\sin^2 2\theta_{13}$ sensitivity below 0.01, while the RENO experiment in Korea [42] should reach a sensitivity around 0.02.

A sketch of $\theta_{13}$ discovery potential of future experiments as a function of the time, following the schedule reported in the experimental proposals, is reported in Figure 4 [32].

**Figure 4.** Evolution of the $\theta_{13}$ discovery potential as a function of time ($3\sigma$ CL) for NH, showing the global sensitivity reach. The bands for the beams and the global reach reflect the (unknown) true value of $\delta$. From [32].
errors.

Proposals for this very challenging task are based 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) [24] and gigantic (megaton scale) neutrino detectors must be built.

Phase II of the T2K experiment, often called T2HK [44], 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, HyperKamiokande or HK, to be built close to SuperKamiokande. An evolution of T2HK is the T2KK [45] 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. Possibilities of intermediate baselines and liquid argon detectors have also been studied [46].

A wide-band beam (WBB) has been proposed at Fermilab upgrading the FNAL main injector after the end of the Tevatron programme [47]. A conventional wide-band neutrino would be sent to a megaton water Čerenkov (or liquid argon) detector at the Homestake mine at a baseline of 1290 km. It would be then displaced at the second oscillation maximum.

In Europe, the perspectives for a high intensity neutrino experiment based on Superbeams 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.

3.1.1. CNGS Upgrades

The CNGS at nominal intensity can be operated to accumulate $4.5 \times 10^{19}$ pot/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 [48] 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 $1 \times 10^{20}$ pot/y. At a longer timescale (>2016), the replacement of the PS with a new 50 GeV synchrotron (PS2 [49]) 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 $2 \times 10^{20}$ pot/y ($6.6 \times 10^{20}$ NOVA pot/y).

Studies about performances of CNGS upgrades with a new setup firing a lower energy neutrino beam off-axis to a 100 kton [50] or 20 kton [51] near the LNGS show anyway that only a proton intensity one order of magnitude higher than present CNGS configuration could allow a sensitive search for leptonic CP violation. This would require a complete refurbishment of the SPS accelerator.

3.1.2. CERN-SPL

In the CERN-SPL super beam project [52] the planned 4MW SPL (Superconducting Proton Linac) would deliver a 3.5 GeV/c $\bar{H^-}$ beam on a Hg target to generate a neutrino beam with an average energy of ~ 0.3 GeV.

The $\nu_e$ contamination from $K$ will be suppressed by threshold effects and the resulting $\nu_e/\nu_\mu$ ratio (~ 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 $\nu_\mu$-disappearance and $\nu_\mu \rightarrow \nu_e$ 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, has been extensively studied [53, 54, 55, 56]. The most updated sensitivity estimations for this setup have been published in Ref. [57].

The MEMPHYS (Megaton Mass Physics) detector [58] 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 [59].

3.1.3. CERN-PS2 It has been proposed in [60] 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 then be 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 [61] 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.

3.2. New Concepts on Neutrino Beams

The super beam approach can be quite powerful if $\theta_{13}$ happens to be sufficiently large, in the range of values that would permit a discovery by the T2K, NO$\nu$A or 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 $\nu_e$ produced by the decay-in-flight of the kaons and muons. When seeking for sub-dominant $\nu_\mu \rightarrow \nu_e$ transitions, the systematics on the knowledge of the $\nu_e$ contamination will likely be the main limitation for a precise determination of CP violation in the leptonic sector [36]. Furthermore 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 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 [62], or within beta decaying ion lifetimes, bringing to the Beta Beam [63, 64].

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 $\gamma$.
- The energy shape of the neutrino beam would be defined by just two parameters, the end-point energy $Q_\beta$ of the beta decaying parent and its Lorentz boost factor $\gamma$.
- 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 and it has been noted very early that their decays might produce useful beams of $\nu_\mu$ and $\bar{\nu}_e$ (exploiting $\mu^-$ decays into $e^-\bar{\nu}_e\nu_\mu$) or $\bar{\nu}_\mu$ and $\nu_e$ ($\mu^+$ decays into $e^+\nu_e\bar{\nu}_\mu$).
In the modern formulation of the “Neutrino Factory” concept, 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 to the desired direction\[62\]. Since $\mu^+$ decay into $e^+\nu_e\bar{\nu}_\mu$, it is possible to investigate $\nu_e \rightarrow \nu_\mu$ oscillations seeking for the appearance of $\mu^-$ from unoscillated $\nu_\mu$ (the same applies to $\mu^-$ decays).

The simultaneous exploitation of $\mu^-$ and $\mu^+$ decays would be an ideal tool to address CP violation in the leptonic sector, with outstanding performances compared with pion-based sources [65]. Moreover, the neutrino factory concept resonated with the needs of the Muon Collider accelerator community, who appreciated the possibility of a strong physics-motivated intermediate step before facing the enterprise of the Muon Collider itself [66].

The realization of the neutrino factory still represents a major accelerator challenge compared with Superbeams. It is met through a world-wide R&D programme; in Europe this programme is especially fostered by UK. Among the Neutrino Factory-oriented projects can be recalled 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 Neutrino Factory has to be seeded by a very powerful low-energy proton accelerator (4 MW); its realization requires similar R&D as for the Superbeams, although its optimal energy lies 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) [67, 68, 69], there is a rather widespread consensus on the fact that the Neutrino Factory can be considered the most performing facility for the determination of $\theta_{13}$, CP violation and the mass hierarchy. With respect to Superbeams, they profit from 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
$\nu_\mu$ 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 1.2. The ISS suggests as an ideal solution the positioning of two detectors at baseline around 3000 and 7000 km.

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, the time schedule for its realization and the cost estimate are vague ($\sim 2020$ after an investment of 1-2 Billion$)$. On the other hand, a clear indication on the size of $\theta_{13}$ will enormously boost the interest of particle physics on this technology. Neutrino Factories are virtually capable of performing real precision physics on the leptonic mixing in a way that resembles the former physics potential of the b-factories on quark mixing.

3.4. Beta Beams
The enormous progress in the technology of Radioactive Ion Beams has led P. Zucchelli [63] to the proposal of a neutrino facility based on the decay in flight of $\beta$-unstable ions (for a full review see [64]). Unlike the Neutrino Factory, these Beta Beams (BB) are pure sources of $\bar{\nu}_e$ or, in the occurrence of $\beta^+$ decays, of $\nu_e$. Hence, they are ideal tools to study $\nu_e \rightarrow \nu_\mu$ transitions and their CP-conjugate exploiting a nearly complete absence of systematics in the knowledge of the source with the bonus of no “right sign muon” background (no $\nu_\mu$ in the initial state). On the other hand, due to the very different mass-to-charge ratio between muons and $\beta$-unstable ions, the energy of the neutrinos are typically much smaller than what can be obtained at the Neutrino Factory.

The original proposal of [63] 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 $\bar{\nu}_e$ and $\nu_e$ sources respectively. It goes without saying that the beta beamtriggered the interest of nuclear physics community, which was offered a stimulating synergy with the neutrino programme at CERN. As a result, such proposal [70] was studied in a systematic manner within the framework of the EURISOL

Figure 6. Layout of a Beta Beam facility
Design Study\(^1\) (Task 12: Beta Beam aspects). The study aimed at \(2.9 \times 10^{18}\) antineutrinos per year from \(^{6}\)He and \(1.1 \times 10^{18}\) neutrinos per year from \(^{18}\)Ne. The outcome was extremely encouraging.

As in the case of the SPL-super beam 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 \(57\) sensitivity on sign(\(\Delta m^2_{23}\)) would be partially recovered by the synergic combination of beam neutrinos with atmospheric neutrinos detected by MEMPHYS \(58\). 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 \(56\). This is possible because radioactive ion production requires a proton source of about 0.2 MW while the SPL could deliver up to 4 MW of power. Furthermore the two neutrino beams 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 \(\nu_\mu \rightarrow \nu_\tau \; \mathrm{vs} \; \overline{\nu}_\mu \rightarrow \overline{\nu}_\tau\) and \(\nu_\mu \rightarrow \nu_\mu \; \mathrm{vs} \; \overline{\nu}_e \rightarrow \overline{\nu}_\mu\)), they can be mixed to study T transitions (like \(\nu_\mu \rightarrow \nu_e \; \mathrm{vs} \; \nu_\tau \rightarrow \nu_\mu\) and \(\overline{\nu}_\mu \rightarrow \overline{\nu}_e \; \mathrm{vs} \; \overline{\nu}_\tau \rightarrow \overline{\nu}_\mu\)) or can be mixed to study CPT transitions (like \(\nu_\mu \rightarrow \nu_e \; \mathrm{vs} \; \overline{\nu}_e \rightarrow \overline{\nu}_\mu\) and \(\nu_\tau \rightarrow \nu_\mu \; \mathrm{vs} \; \overline{\nu}_\mu \rightarrow \overline{\nu}_e\)).

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 \(\theta_{23}\) and \(\Delta m^2_{23}\) and the lack of \(\nu_\mu\) events in the close detector, useful for calibrating beta beam signal efficiency and measuring the \(\nu_\tau/\nu_\mu\) cross section ratio.

To improve the performances of the Eurisol Beta Beam several alternatives to the SPS have been considered: a refurbished 1 TeV SPS ("SuperSPS" \(71\)) envisaged for the energy and luminosity upgrade of the LHC or even the LHC itself \(72, 73, 74, 75\), an option that nowadays seems far in the future if not unlikely.

In 2006, C. Rubbia et al. \(76\) proposed the use of \(^8\)Li and \(^8\)B as neutrino sources noting that these isotopes could be produced in a multturn 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 \(\sim 0.5\) to \(\sim 1.5\) GeV for the SPS-based BB). This alternative approach is at focus in the framework of the EURO\(\nu\) Design Study\(^2\).

A drawback with respect to the use of low-Q ions is that the flux at the far location is smaller due to the larger beam divergence and a larger amount of ions stacked in the decay ring is needed. More generally the performances of a Beta Beam in delivering neutrinos can be parametrized with a merit factor \(M \propto \frac{Q_\beta}{Q_3}\) \(64\) from which it follows that performances of a beta beam scale as the Lorentz boost factor \(\gamma\) and are inversely proportional to the endpoint energy \(Q_\beta\). For this reason for the same baseline an high-Q beta beam requires about an order of magnitude more ions at the source to match the performances of the Eurisol-\(\gamma\) beta beam.

A further option for beta beams is the possibility of creating monochromatic neutrino beams \(78\). These beams are based on electron capture processes of radioactive ions, rather

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\(^1\) The EURISOL Design Study was a Project funded by the European Community within the 6th Framework Programme as a Research Infrastructures Action under the "Structuring the European Research Area Specific Programme". The Project started officially on Feb 2005, and has been completed on spring 2009.

\(^2\) EURO\(\nu\) \(77\) is a FP7 Design Study which started on Sept 2008 and will run for 4 years. The primary aims are to study three possible future neutrino oscillation facilities for Europe (a Superbeam from CERN-to-Frejus, a RAL or CERN based Neutrino Factory and high-Q BB) and do a cost and performance comparison.
than on their beta decays, producing monochromatic neutrino beams. The main limitations of these setups are the technical difficulties of the production and acceleration schemes and the impossibility of having monochromatic antineutrino beams.

Low energy beta beams, producing neutrinos with energies in the range of few tens of MeV, could offer interesting non-oscillation neutrino physics measurements, as discussed in [79].

Concluding, beta beam performance are in between the performance 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 Neutrino Factory 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, see Fig. 7, 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.

Ultimate performances can be reached by the neutrino factory. However, if $\theta_{13}$ 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.
5. CPT in the neutrino sector

A motivation to look for signals of CPT and Lorentz invariance violation in the neutrino sector is the possibility of a different mechanism for generating the small neutrino masses (compared to the masses of quarks and charged leptons), the so-called seesaw mechanism [83, 84, 85]. If neutrino masses are generated at energies approaching the Plank scale, they could be sensitive to new physics [86].

A consequence of CPT violation would be a difference between the parameters governing the oscillations of neutrinos and antineutrinos. A global fit to neutrino oscillations performed separating the terms coming from neutrino oscillations from those coming from antineutrino oscillations [87] (updated results have been shown in [88]) showed that at present no indication of CPT violation emerges from the global data, although the sensitivity of these comparison is quite poor.

Some renewed interest to CPT violation in the neutrino sector has been raised by the preliminary results, still not published, of the MINOS collaboration about a difference of $2.4\Delta m^2$ required by this experimental result. This possibility had been excluded by the fits of [87]. It has been also been advocated to save the sterile neutrino “3+1” model against the negative evidence of short baseline reactor neutrino experiments [94]. As discussed in Sec. 1, the bound of reactor neutrino experiments is now an evidence in favor to sterile neutrinos and steriles alone seem to be enough to describe the global data on neutrino oscillations [21].

Future neutrino facilities as those discussed in the previous sections could be a powerful tool to improve the sensitivity on CPT violation in the neutrino sector, as discussed in [95].

Finally, following the discussion of [90] there are other two kind of CPT tests that can be performed by neutrino oscillation experiments:

(i) Searches for Lorentz-violating effects in concert with CPT violation. Limits have been recently published by the LSND [96], MINOS [97] and IceCube [98] experiments.

(ii) Searches for inconsistencies in oscillation results that could point to baseline-dependent new physics with possible ramifications for CPT. They have been discussed in [99, 100, 101].

References
[1] Fukuda Y et al. (Super-Kamiokande) 1998 Phys. Rev. Lett. 81 1562–1567 (Preprint hep-ex/9807003)
[2] Ambrosio M et al. (MACRO Collaboration) 2003 Phys. Lett. B566 35–44 (Preprint hep-ex/0304037)
[3] Alnu E et al. (K2K) 2005 Phys. Rev. Lett. 94 081802 (Preprint hep-ex/0411038)
[4] Michael D G et al. (MINOS) 2006 Phys. Rev. Lett. 97 191801 (Preprint hep-ex/0607088)
[5] Ahmad Q R et al. (SNO) 2002 Phys. Rev. Lett. 89 011301 (Preprint nucl-ex/0204008)
[6] Cleveland B T et al. 1989 Astrophys. J. 406 505–526
[7] Hirata K et al. (KAMIOKANDE-II Collaboration) 1989 Phys. Rev. Lett. 63 16
[8] Abe K et al. (Super-Kamiokande Collaboration) 2010 Long author list - awaiting processing (Preprint 1010.0118)
[9] Anselmann P et al. (GALLEX Collaboration) 1992 Phys. Lett. B285 376–389
[10] Altmann M et al. (GNO) 2005 Phys. Lett. B616 174–190 (Preprint hep-ex/0504037)
[11] Abazov A, Abdurashtov D, Anosov O, Eroshkina L, Faizov E et al. 1991 Nucl. Phys. Proc. Suppl. 19 84–93
[12] Abdurashtov J et al. (SAGE Collaboration) 2009 Phys. Rev. C80 015807 (Preprint 0901.2200)
[13] Eguchi K et al. (KamLAND Collaboration) 2003 Phys. Rev. Lett. 90 021802 (Preprint hep-ex/0212021)
[14] Schwetz T, Tortola M A and Valle J W F 2008 New J. Phys. 10 113011 (Preprint 0808.2016)
[15] Aguilar A et al. (LSND Collaboration) 2001 Phys. Rev. D64 112007 (Preprint hep-ex/0104049)
[16] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2009 Phys. Rev. Lett. 103 111801 (Preprint 0904.1958)
[59] Antier D et al. 2007 JCAP 0711 011 (Preprint 0705.0116)
[60] Rubbia A 2010 A CERN-based high-intensity high-energy proton source for long baseline neutrino oscillation experiments with next-generation large underground detectors for proton decay searches and neutrino physics and astrophysics (Preprint 1003.1921)
[61] Large apparatus studying grand unification and neutrino astrophysics http://www.laguna-science.eu/
[62] Geer S 1998 Phys. Rev. D57 6989–6997 (Preprint hep-ph/9712290)
[63] Zucchelli P 2002 Phys. Lett. B532 166–172
[64] Lindroos M and Mezzetto M 2009 Beta beams: Neutrino beams London, UK: Imperial College Pr., 154 p
[65] De Rujula A, Gavela M B and Hernandez P 1999 Nucl. Phys. B547 21–38 (Preprint hep-ph/9811390)
[66] Geer S 2009 Ann. Rev. Nucl. Part. Sci. 59 347–365
[67] Berg J S et al. (ISS Accelerator Working Group) 2009 JINST 4 P07001 (Preprint 0802.4023)
[68] Bandyopadhyay A et al. (ISS Physics Working Group) 2009 Rept. Prog. Phys. 72 106201 (Preprint 0710.4947)
[69] Abe T et al. (ICE-Cube Collaboration) 2007 Phys. Rev. D80 0710.4947
[70] Bouchez J, Lindroos M and Mezzetto M 2004 AIP Conf. Proc. 721 37–47 (Preprint hep-ex/0310059)
[71] Bruning O et al. Lhc luminosity and energy upgrade: A feasibility study. CERN-LHC-PROJECT-REPORT-626;
[72] Burguet-Castell J, Casper D, Gomez-Cadenas J J, Hernandez P and Sanchez F 2004 Nucl. Phys. B695 217–240 (Preprint hep-ph/0312068)
[73] Terranova F, Marotta A, Migliozzi P and Spinetti M 2004 Eur. Phys. J. C38 69–77 (Preprint hep-ph/0405081)
[74] Agarwalla S K, Raychaudhuri A and Samanta A 2005 Phys. Lett. B629 33–40 (Preprint hep-ph/0505015)
[75] Donini A, Fernandez-Martinez E, Migliozzi P, Rigolin S, Lavina L et al. 2008 Eur. Phys. J. C53 599–606 (Preprint hep-ph/0703209)
[76] Rubbia C, Ferrari A, Kadi Y and Vlachoudis V 2006 Nucl. Instrum. Meth. A568 475–487 (Preprint hep-ph/0602032)
[77] European commission fp7 design study: A high intensity neutrino oscillation facility in europe http://www.euronu.org
[78] Bernabeu J, Burguet-Castell J, Espinoza C and Lindroos M 2005 JHEP 12 014 (Preprint hep-ph/0505054)
[79] Volpe C 2007 J. Phys. G34 R1–R44 (Preprint hep-ph/0605033)
[80] Barger V, Huber P, Marfatia D and Winter W 2007 Phys. Rev. D76 053005 (Preprint hep-ph/0703209)
[81] Choubey S, Coloma P, Donini A and Fernandez-Martinez E 2009 JHEP 12 020 (Preprint 0907.2379)
[82] Bross A D, Ellis M, Geer S, Mena O and Pascoli S 2008 Phys. Rev. D77 093012 (Preprint 0709.3889)
[83] Gell-Mann M, Ramond P and Slansky R 1979 Supergravity, ed. by F. van Nieuwenhuizen and D. Freedman (Amsterdam, North Holland, 1979) 315
[84] Yanagida T 1980 Prog. Theor. Phys. 64 1103
[85] Mohapatra R N and Senjanovic G 1980 Phys. Rev. Lett. 44 912
[86] Kostelecky V and Mewes M 2004 Phys. Rev. D70 031902 (Preprint hep-ph/0308300)
[87] Gonzalez-Garcia M C and Magon C 2007 Phys. Rept. 460 1–129 (Preprint 0704.1800)
[88] Maltoni M New Physics in the Atmospheric Sector: non-Standard Interactions and CPT Violation presentation at the XIV Int. Workshop on Neutrino Telescopes, Venezia, March 15-18, 2011
[89] Danko I (MINOS Collaboration) 2009 (Preprint 0910.3439)
[90] Barenboim G and Lykken J D 2009 Phys. Rev. D80 113008 (Preprint 0908.2993)
[91] Kopp J, Machado P A and Parke S J 2009 Phys. Rev. D82 113002 (Preprint 1009.0014)
[92] Engelhardt N, Nelson A E and Walsh J R 2010 Phys. Rev. D81 113001 (Preprint 1002.4452)
[93] Murayama H and Yanagida T 2001 Phys. Lett. B520 263–268 (Preprint hep-ph/010178)
[94] Giunti C and Laveder M 2010 Phys. Rev. D82 113009 (Preprint 1008.4750)
[95] Antusch S and Fernandez-Martinez E 2008 Phys. Lett. B665 190–196 (Preprint 0804.2820)
[96] Adamson P et al. (IceCube Collaboration) 2010 Phys. Rev. Lett. 105 151601 (Preprint 1007.2791)
[97] Abbasi R et al. (IceCube Collaboration) 2010 Phys. Rev. D82 112003 (Preprint 1010.4096)
[98] Mavromatos N E, Meregaglia A, Rubbia A, Sakharov A and Sarkar S 2008 Phys. Rev. D77 053014 (Preprint 0801.0872)
[99] Sakharov A, Mavromatos N, Meregaglia A, Rubbia A and Sarkar S 2009 J. Phys. Conf. Ser. 171 012038 (Preprint 0903.4985)
[100] Hollenberg S, Micu O, Pas H and Weiler T J 2009 Phys. Rev. D80 093005 (Preprint 0906.0150)