ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2011. Т. 42. ВЫП. 4

FUTURE NEUTRINO LONG BASELINE EXPERIMENTS

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Very soon a new generation of reactor and accelerator neutrino oscillation experiments — Double Chooz, Daya Bay, Reno, and T2K — will seek for oscillation signals generated by the mixing parameter θ_{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 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 counterpart of the Cabibbo–Kobayashi–Maskawa matrix.

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1. NEUTRINO OSCILLATIONS

Neutrino oscillations experiments had been very succesful in the past 15 years. Neutrino oscillations had been discovered in 1998 by the SuperKamiokande experiment [1] by analyzing atmospheric neutrinos. The measurement had been confirmed by Macro [2] and Soudan II [3]. The same oscillations had been then measured by exploiting artificial neutrino beams by the K2K [4] and MINOS [5] experiments. In 2002, the SNO experiment [6] 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 [7] and continued by the two gallium experiments Gallex–GNO [9] and Sage [10] and by SuperKamiokande [8]. Soon after SNO, the KamLAND [11] 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 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, ν_μ, and ν_τ by a mixing matrix U. The neutrino oscillation probability depends on three mixing angles, θ_{12}, θ_{23}, θ_{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 δ_{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 at different CL, as obtained in [12], are shown in the Table.

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 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 Δm^2_{23}. Its value could be $+1$ (normal hierarchy), in which case ν_e would be the lightest neutrino, or -1 (inverted hierarchy), for which ν_e would be the heaviest. Its value is of great importance for double-beta decay experiments [13] and it could shed light on possible flavour symmetries.

The CP phase δ_{CP} is the ultimate goal of neutrino oscillation searches. The demonstration of CP violation in the lepton sector (LCPV) 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 [14].

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.

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 [12]

Parameter	Best fit	2σ	3σ
Δm^2_{21}, 10^{-5} eV^2	$7.59^{+0.23}_{-0.18}$	7.22–8.03	7.03–8.27
$\lvert\Delta m^2_{31}\rvert$, 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
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	$\leqslant 0.039$	$\leqslant 0.053$

1.1. Subleading $\nu_\mu \to \nu_e$ Oscillations. The $\nu_\mu \to \nu_e$ transition probability in case of small matter effects can be parameterized as [15]:

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E_\nu} \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] +$$
$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23})\times$$
$$\times \cos\frac{\Delta m_{23}^2 L}{4E_\nu} \sin\frac{\Delta m_{13}^2 L}{4E_\nu} \sin\frac{\Delta m_{12}^2 L}{4E_\nu} \mp$$
$$\mp 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23} \sin\delta_{CP} \sin\frac{\Delta m_{23}^2 L}{4E_\nu} \sin\frac{\Delta m_{13}^2 L}{4E_\nu} \sin\frac{\Delta m_{12}^2 L}{4E_\nu} +$$
$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13} \cos\delta_{CP}\} \sin\frac{\Delta m_{12}^2 L}{4E_\nu} \mp$$
$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu} \sin\frac{\Delta m_{13}^2 L}{4E_\nu} \frac{aL}{4E_\nu}(1-2s_{13}^2). \quad (1)$$

The first line of this parameterization contains the term driven by θ_{13}, the second and third contain CP even and odd terms, respectively, and the fourth is driven by the solar parameters. The last line parameterizes matter effects developed at the first order where $a[\mathrm{eV}^2] = \pm 2\sqrt{2} G_F n_e E_\nu = 7.6{\cdot}10^{-5} \rho[\mathrm{g/cm}^3]$ $E_\nu[\mathrm{GeV}]$. The «$\pm$» and «$\mp$» terms refer to neutrinos and antineutrinos, respectively. A sketch of $P(\nu_\mu \to \nu_e)$ as a function of L for 1 GeV neutrinos is shown in Fig. 1.

θ_{13} searches look for experimental evidence of ν_e appearance in excess of what is expected from the solar terms. These measurements will be experimentally hard because the present limit on θ_{13}, summarized in the Table, translates into a

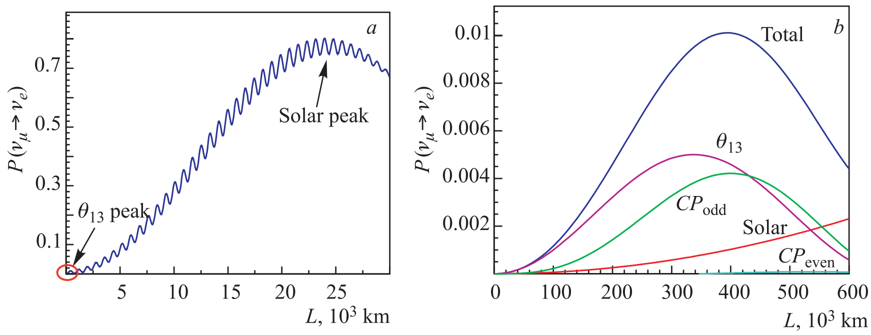

Fig. 1. Sketch of $P(\nu_\mu \to \nu_e)$ as a function of the baseline computed for monochromatic neutrinos of 1 GeV in the solar baseline regime for $\delta_{CP} = 0$ (a) and in the atmospheric baseline regime for $\delta_{CP} = -\pi/2$ (b), where the different terms of Eq. (1) are displayed. The following oscillation parameters were used in both cases: $\sin^2 2\theta_{13} = 0.01$, $\sin^2 2\theta_{12} = 0.8$, $\Delta m_{23}^2 = 2.5{\cdot}10^{-3}$ eV^2, $\Delta m_{12}^2 = 7{\cdot}10^{-5}$ eV^2. From [16]

$\nu_\mu \to \nu_e$ appearance probability smaller than 10% at the appearance maximum in a high-energy muon neutrino beam. When matter effects are not negligible, following Eq. (1) of [17], the transition probability $\nu_e \to \nu_\mu$ ($\bar{\nu}_e \to \bar{\nu}_\mu$) at second order in perturbation theory in θ_{13}, $\Delta m^2_{12}/\Delta m^2_{23}$, $|\Delta m^2_{12}/a|$ and $\Delta m^2_{12} L/E_\nu$ (see also [18]) is:

$$P^{\pm}(\nu_e \to \nu_\mu) = X_\pm \sin^2(2\theta_{13}) + Y_\pm \cos(\theta_{13}) \sin(2\theta_{13}) \cos\left(\pm\delta - \frac{\Delta m^2_{23} L}{4E_\nu}\right) + Z, \quad (2)$$

where «$\pm$» refers to neutrinos and antineutrinos, respectively. The coefficients of the two equations are:

$$X_\pm = \sin^2(\theta_{23}) \left(\frac{\Delta m^2_{23}}{|a - \Delta m^2_{23}|}\right)^2 \sin^2\left(\frac{|a - \Delta m^2_{23}| L}{4E_\nu}\right),$$
$$Y_\pm = \sin(2\theta_{12}) \sin(2\theta_{23}) \left(\frac{\Delta m^2_{12}}{a}\right) \left(\frac{\Delta m^2_{23}}{|a - \Delta m^2_{23}|}\right) \sin\left(\frac{aL}{4E_\nu}\right) \sin\left(\frac{|a - \Delta m^2_{23}| L}{4E_\nu}\right), \quad (3)$$
$$Z = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \left(\frac{\Delta m^2_{12}}{a}\right)^2 \sin^2\left(\frac{aL}{4E_\nu}\right)$$

(remember that a changes sign by changing neutrinos with antineutrinos and that $P(\nu_e \to \mu_\mu, \delta_{CP}) = P(\nu_\mu \to \nu_e, -\delta_{CP})$).

One of the interesting aspects of Eq. (2) is the occurrence of matter effects which, unlike the straightforward θ_{13} term, depends on the sign of the mass difference sign (Δm^2_{23}). These terms should 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 very different neutrino energy dependence, matter effects being larger for higher energies, with a «matter resonance» at about 12 GeV.

At 130 km, matter effects are negligible, Fig. 2, a. Inverse hierarchy solutions are very similar to direct hierarchy (to change the sign of δ_{CP} is equivalent to change the sign of Δm^2_{23}). For this reason there will not be degeneracies for CP searches but also the sensitivity on mass hierarchy will be very small. At 730 km, matter effects are sizable, Fig.2, b, and probabilities differ. Note, however, as the normal hierarchy $\delta_{CP} = 0$ probability is very similar to inverse hierarchy $\delta_{CP} = \pi/2$, it would be very difficult to experimentally disentangle the two.

At 2500 km where the matter effects are bigger, Fig. 2, c, note how the two probabilities are more different and how their behaviour is very much different at the second oscillation maximum.

This fact does not come for free. Neutrino fluxes go like $1/L^2$ and so the flux at 2500 km is about ten times smaller than the flux at 730 km. A par-

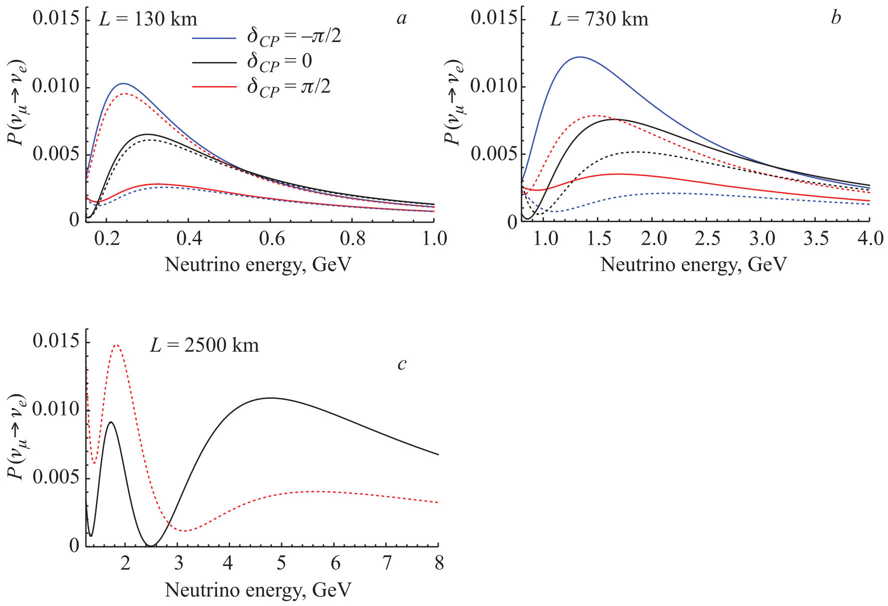

Fig. 2. Probaility of oscillation computed at the baselines of 130 km (a), 730 km (b) and 2500 km (c) as a function of the neutrino energy. Solid curves are computed for the normal hierarchy; dashed curves, for inverted hierarchies. The three sets of curves refer to three values of δ_{CP}: 0, $\pi/2$, and $-/\pi/2$. The other oscillation parameters are set to the values of the Table while θ_{13} is set to $\theta_{13} = 3°$. For the baseline of 2500 km, only the two curves for $\delta_{CP} = \pi/2$ normal hierarchy and the $\delta_{CP} = \pi/2$ inverted hierarchy are displayed

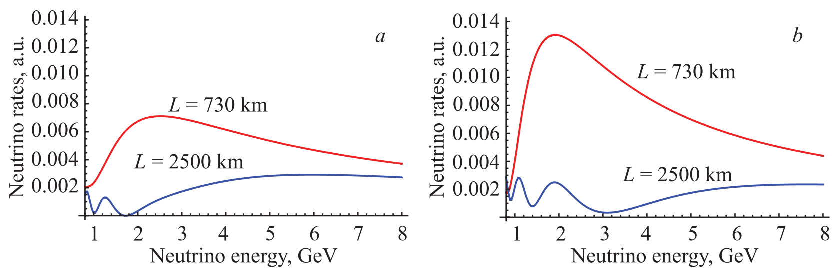

Fig. 3. Plots of the product of oscillation probability times cross section times the inverse of solid angle computed, in arbitrary units, as a function of the neutrino energy for the baselines of 730 and 2500 km for the normal hierarchy (a) and the inverse one (b). The oscillation parameters are set to the values of Fig. 2

tial compensation comes from the rise of the neutrino interaction cross sections $\sigma \propto E$. A comparison of interaction rates $I \propto P \times \sigma \times L^{-2}$ shows, Fig. 3, which great sacrifice in statistics is required to have access to $\mathrm{sign}\,(\Delta m^2_{23})$ sensitivity. The great difference between neutrino rates computed with the normal and inverted hierarchy, demonstrates that even at the second oscillation maximum both the neutrino and the antineutrino beams will be necessary.

1.2. Leptonic CP Violation. The ultimate challenge of oscillation neutrino physics will be to determine weather CP is violated or not in neutrino oscillations. The experimental information relies on the fact that some term in Eqs. (1), (2) changes sign by exchanging neutrinos with antineutrinos. In this way the probability of oscillation for neutrino will result different from the probability of antineutrinos. This allow one to build a CP-violating asymmetry A_{CP}:

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \qquad (4)$$

displayed in Fig. 4 as a function of θ_{13}, or the equivalent time reversal asymmetry A_T.

The richness of the $\nu_\mu \to \nu_e$ 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 multidimensional 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 [17]; the hierarchy or $\mathrm{sign}\,(\Delta m^2_{23})$-degeneracy [21]; the octant or

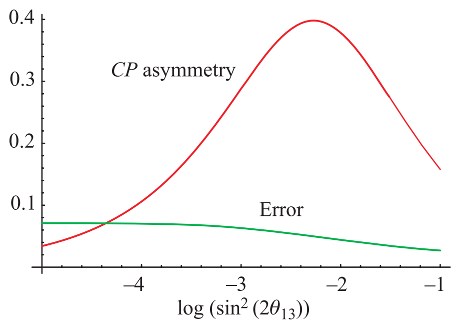

Fig. 4. Magnitude of the CP asymmetry at the first oscillation maximum, for $\delta = 1$ as a function of the mixing angle $\sin^2 2\theta_{13}$. The curve marked «error» indicates the dependence of the statistical + systematic error on such a measurement. The curves have been computed for the baseline beta beam option at the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km, statistical $+2\%$ systematic errors. From [19]

θ_{23}-degeneracy [20]. These lead to an eightfold ambiguity in θ_{13} and δ_{CP} [22], and hence degeneracies provide a serious limitation for the determination of θ_{13}, δ_{CP}, and sign (Δm^2_{23}).

2. SEARCHES FOR NONVANISHING VALUES OF θ_{13}

The first objective of neutrino oscillation experiments is to look for nonvanishing 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 [23, 24].

Accelerator experiments can measure θ_{13} by detecting the appearance of ν_e neutrinos in accelerator neutrino beams, see Eq. (2). The determination of θ_{13} will be highly influenced by the unknown value of δ_{CP} and sign (Δm^2_{23}). This will weaken the limits on θ_{13} in case of no signal or the precision of its determination in case of a signal.

Neutrino beams are produced, see Fig. 5, 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_μs ($\overline{\nu}_\mu$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 [25] measured both the K2K [26] and the MiniBooNE [27] 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 [28]).

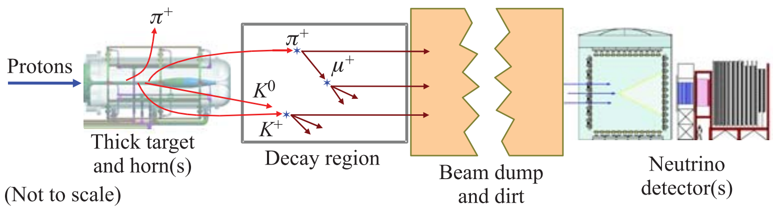

Fig. 5. Sketch of a conventional accelerator neutrino beam line

The T2K (Tokai to Kamioka) experiment [29] will aim neutrinos from the Tokai site of J-PARC (30 GeV, 0.75 MW) to the SuperKamiokande detector 295 km away. The neutrino beam is situated at an off-axis angle of 2.5°, 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 $\sin^2 2\theta_{13} \leqslant 0.006$ (90% CL).

The NOνA experiment with an upgraded NuMI off-axis neutrino beam [30] ($E_\nu \sim 2$ GeV and a ν_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 $\nu_\mu \to \nu_e$ oscillations with a θ_{13} sensitivity similar to T2K and with some sensitivity to $\mathrm{sign}\,(\Delta m^2_{23})$ thanks to the longer baseline.

Another approach to searching for nonvanishing 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 [31] 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

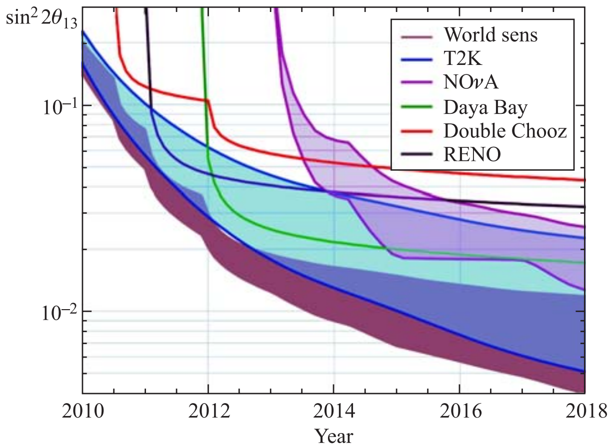

Fig. 6. Evolution of the θ_{13} discovery potential as a function of time (3σ CL) for NH, showing the global sensitivity reach. The bands for the beams and the global reach reflect the (unknown) true value of δ. From [24]

90% CL. The Daya Bay project in China [32] could reach a $\sin^2 2\theta_{13}$ sensitivity below 0.01, while the RENO experiment in Korea [33] should reach a sensitivity around 0.02.

A sketch of θ_{13} discovery potential of future experiments as a function of the time, following the schedule reported in the experimental proposals, is reported in Fig. 6 [24].

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 or $\mathrm{sign}\,(\Delta m^2_{23})$ [34] 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.

Proposals for this very challenging task are based either on conventional neutrino beams pushed to their ultimate power, Subsec. 3.1, or to innovative conceps about neutrino production, Subsec. 3.2.

3.1. Neutrino Superbeams. To fulfill the needs of searches for leptonic CP violation, conventional neutrino beams must be pushed to their ultimate limits (neutrino superbeams) [15], and gigantic (megaton scale) neutrino detectors must be built.

Phase II of the T2K experiment, often called T2HK [35], 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 [36] 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 been also studied [37]

A wide-band beam (WBB) has been proposed at Fermilab upgrading the FNAL main injector after the end of the Tevatron programme [38]. 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 wuold be then displaced at the second oscillation maximum, a configuration discussed in Subsec. 1.1.

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 superbeams based on upgrades of the CNGS, Subsubsec. 3.1.1, on a high power SPL, Subsubsec. 3.1.2, or on a high power PS2, Subsubsec. 3.1.3, have been studied.

3.1.1. CNGS Upgrades. The CNGS at nominal intensity can be operated to accumulate $4.5 \cdot 10^{19}$ 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 [39] 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 is 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 $1 \cdot 10^{20}$ pot/y ($3.3 \cdot 10^{20}$ NOVA pot/y). At a longer timescale (> 2016), the replacement of the PS with a new 50 GeV synchrotron (PS2 [40]) might surpass these limitations, provided an appropriate upgrade of the SPS radio-frequency system.

It would bring CNGS to a maximum intensity (CNGS as the only user of the SPS beyond the LHC) of $2 \cdot 10^{20}$ pot/y ($6.6 \cdot 10^{20}$ NOVA pot/y).

Studies about performances of CNGS upgrades with a new setup firing a lower energy neutrino beam off-axis to a 100 kt [41] or 20 kt [42] near the LNGS show anyway that only with a proton intensity one order of magnitude higher than the present CNGS configuration could allow a sensitive search for leptonic CP violation. This would require a complete refurbishement of the SPS accelerator.

3.1.2. CERN–SPL. In the CERN–SPL superbeam project [43] the planned 4MW SPL (Superconducting Proton Linac) would deliver a 3.5 GeV/c H^- beam on a Hg target to generate a neutrino beam with an average energy of ~ 0.3 GeV.

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 superbeam (SPL–SB) with a water Čerenkov far detector with a fiducial mass of 440 kt, has been extensively studied [45, 46]. The most updated sensitivity estimations for this setup have been published in [47].

The MEMPHYS (Megaton Mass Physics) detector [48] is a megaton-class water Čerenkov designed to be located at Fréjus, 130 km from CERN, addressing both the nonaccelerator domain (nucleon decay, SuperNovae neutrino from burst event or from relic explosion, solar and atmospheric neutrinos) and the accelerator (superbeam, beta beam) domain [49].

3.1.3. CERN–PS2. It has been proposed in [50] 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 or 1544 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 [49] 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 fullfill the requirements of this configuration. And following the discussion about the WBB, this kind of configuration would have excellent performances in measuring $\mathrm{sign}\,(\Delta m^2_{23})$ but a limited sensitivity for leptonic CP violation and the measurment of θ_{13}.

3.2. New Concepts on Neutrino Beams. The superbeam approach can be quite powerful if θ_{13} happens to be sufficiently large, in the range of values that would permit a discovery by the T2K, NOνA 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 ν_e produced by the decay-in-flight of the kaons and of the muons. When seeking for subdominant $\nu_\mu \to \nu_e$ 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 [28].

• 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 than 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 [51], or within beta decaying ion lifetimes, bringing to the Beta Beam [52, 53].

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.

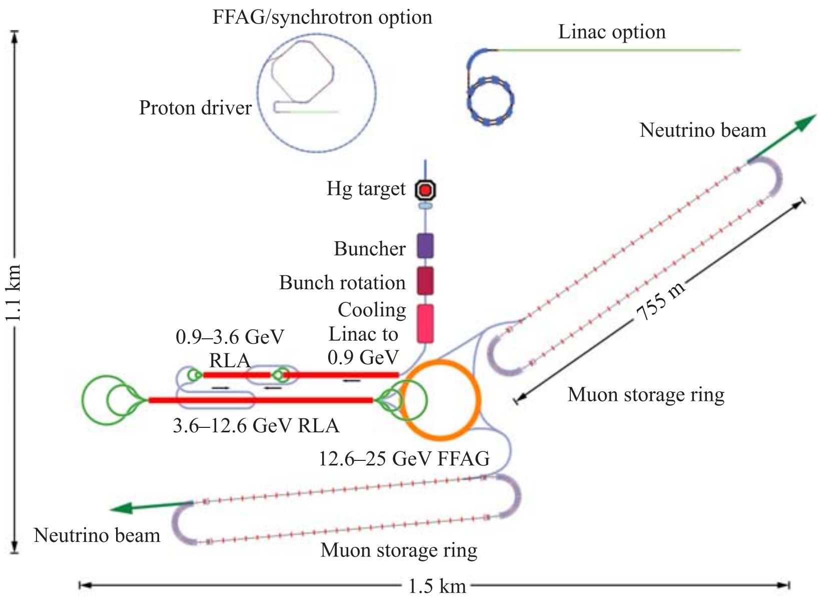

Fig. 7. Layout of a Neutrino Factory facility

• 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 60s and it has been noted very early that 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 $e^+\nu_e\overline{\nu}_\mu$). However, realistic layouts to get intense neutrino sources have become available only in recent times.

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 in the desired direction. In 1997, S. Geer [51] noted that this source could be ideal to study $\nu_e \to \nu_\mu$ oscillations at the atmospheric scale, i.e., the T-conjugate of the channel observed in superbeams ($\nu_e \to \nu_\mu$). Since μ^+ decay into $e^+ \; \nu_e\overline{\nu}_\mu$, 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 we are able to separate these events from the bulk of μ^+ («right sign muons») coming from unoscillated $\overline{\nu}_\mu$.

A. De Rujula et al. [54] underlined that 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. 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.

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 the 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 (radiofrequency and absorbers). Moreover, the NF 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 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) [55–57], there is a rather widespread consensus on the fact that the Neutrino Factory can be considered the most performing facility for the determination of θ_{13}, CP violation and the mass hierarchy (Fig. 7). With respect to superbeams, 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 Subsec. 1.2. 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 $\nu_e \to \nu_\tau$ at baseline around 1000 km («silver channel») [58]. The exploitation of the silver channel, moreover, is useful to investigate the occurrence of non-standard interactions in the neutrino sector [59].

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 θ_{13} will enormously boost the interest of particle physics on this technology. Neutrino Factories are virtually capable of

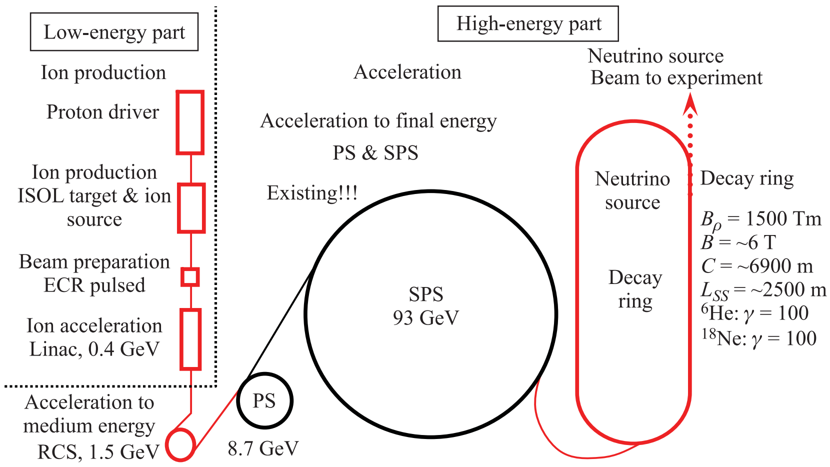

Fig. 8. Layout of the Beta Beam facility

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 [52] to the proposal of a neutrino facility based on the decay in flight of β-unstable ions (for a full review see [53]). 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 is typically much smaller than what can be obtained at the NF.

The original proposal of [52] 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 (Fig. 8). It goes without saying that the BB triggered the interest of nuclear physics community, which was offered a stimulating synergy with the neutrino programme at CERN. As a result, such proposal [48, 60] was studied in a systematic manner within the framework of the EURISOL Design Study* (Task 12: BB aspects). The study aimed at $2.9 \cdot 10^{18}$ antineutrinos per year from ^{6}He and $1.1 \cdot 10^{18}$ neutrinos per year from ^{18}Ne.

*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 in February 2005, and has been completed in spring 2009.

The outcome was 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). Along this line, the most straightforward alternative would be direct production on MgO based on a 2 MW, a few MeV, proton accelerators, which are quite similar to the linacs that have to be built for the International Fusion Materials Irradiation Facility [61]. 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 superbeams 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-superbeam 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 [47], sensitivity on $\mathrm{sign}\,(\Delta m^2_{23})$ would be partially recovered by the synergic 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 [46].

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

The combination of a superbeam 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 $\nu_\mu \to \nu_e$ vs. $\overline{\nu}_\mu \to \overline{\nu}_e$ and $\nu_e \to \nu_\mu$ vs. $\overline{\nu}_e \to \overline{\nu}_\mu$.

• They can be mixed to study T transitions like $\nu_\mu \to \nu_e$ vs. $\nu_e \to \nu_\mu$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ vs. $\overline{\nu}_e \to \overline{\nu}_\mu$.

• They can be mixed to study CPT transitions like $\nu_\mu \to \nu_e$ vs. $\overline{\nu}_e \to \overline{\nu}_\mu$ and $\nu_e \to \nu_\mu$ vs. $\overline{\nu}_\mu \to \overline{\nu}_e$.

The addition of a superbeam 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_μ 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 («Super-SPS» [44]) envisaged for the energy and luminosity upgrade of the LHC or even the LHC itself [62, 63], 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 for the construction of the decay ring since the length of the ring depends on the magnetic rigidity of the circulating ions, which is proportional to their Lorentz γ factor, and for the compensation of potential flux reduction due to the longer lifetime of the ion in the laboratory frame.

In 2006, C. Rubbia et al. [64] 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 BB. 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 Design Study*.

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 it can be defined a merit factor $\mathcal{M}$ [53]

$$\mathcal{M} \propto \frac{\gamma}{Q_\beta} \tag{5}$$

from which it follows that performances of a beta beam scale as the Lorentz boost factor γ and are inversely proportional to the endpoint energy Q_β. For this reason for the same baseline L a high-Q BB needs an order of magnitude more ions at the source to match the performances of a high-γ BB.

A further option for beta beams is the possibility of creating monochromatic neutrino beams [66]. These beams are based on electron capture processes of radioactive ions, rather than on their beta decays, producing monochromatic neutrino beams. This is an extremely interesting setup, since the neutrino detector has only to guarantee a correct particle identification, being the neutrino energy known at the source. The main limitations of these setups are the technical difficulties of the production and acceleration schemes.

Concluding, beta beam performance is in between the performances of superbeams and neutrino factory. The clarification of the issue of the ion production yield is considered a crucial milestone for the BB. 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

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*EUROν [65] is a FP7 Design Study which started in September 2008 and will run for four 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 NF and high-Q BB) and do a cost and performance comparison.

of employing existing facilities (e.g., the CERN PS-SPS complex or its upgrades) might substantially strengthen this option.

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 superbeams, 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. 9, shows that leptonic CP violation can be discovered provided that $\sin^2 2\theta_{13}$ is not four orders of magnitudes below the present experimental limit.

Ultimate performances can be reached by the neutrino factory. However if θ_{13} happens to be on the reach of the next generation experiments, $\sin^2 2\theta_{13} \geqslant 0.01$, superbeams and beta beams could be very competitive being less demanding on R&D developments and costs.

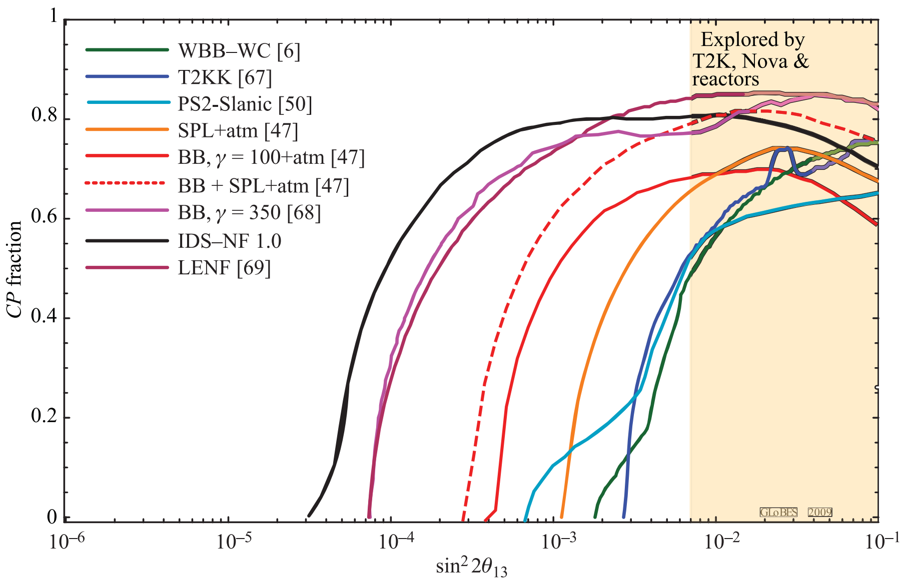

Fig. 9. The discovery reached at 3σ level for different facilities for leptonic CP violation. The discovery limits are shown as a function of the fraction of all possible values of the true value of the CP phase δ and the true value of $\sin^2 2\theta_{13}$. The curves are taken from [34, 47, 50, 67–69]

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