European facilities for accelerator neutrino physics: perspectives for the decade to come

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Abstract

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 $\theta_{13}$. 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. In this paper the status of these studies will be summarized, focusing on the options that are best suited to exploit existing European facilities (firstly CERN and the INFN Gran Sasso Laboratories) or technologies where Europe has a world leadership. Similar considerations will be developed in more exotic scenarios - beyond the standard framework of flavor oscillation among three active neutrinos - that might appear plausible in the occurrence of anomalous results from post-MiniBooNE experiments or the CNGS.

1 Open questions in neutrino oscillations and a glimpse to future

The results of atmospheric, solar, accelerator and reactor neutrino experiments \cite{1} accumulated in the last decades show that flavor mixing occurs not only in the hadronic sector, as it has been known for long, but in the leptonic sector as well. This outstanding result has been obtained exploiting a quantum interference phenomenon speculated by Pontecorvo in 1957 and named - in analogy with the oscillation of neutral K mesons - “neutrino oscillation” \cite{2}. In its modern formulation, neutrino oscillations occur because flavor states generated by weak interactions, i.e. what we call “electron neutrinos” ($\nu_e$), “muon neutrinos” ($\nu_\mu$) and “tau neutrinos” ($\nu_\tau$), are not stationary states but, indeed, a coherent superposition of states with rest mass $m_1$, $m_2$ and $m_3$. As a consequence, flavor evolves with time and neutrinos of a given flavor $\nu_\alpha$ produced from a source at a distance $L$ from the detector, might be measured to have a different flavor $\nu_\beta$. Pontecorvo noted in 1967 that, assuming only two flavors (at that time the tau lepton and the $\nu_\tau$ were still unknown), the probability of observing a $\nu_\beta$ from a pure source of $\nu_\alpha$ is given by:

$$ P(\nu_\beta \rightarrow \nu_\alpha) = \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2 ([eV^2]) L ([km])}{E ([GeV])}, $$

being $\theta$ the angle that parametrizes a rotation between the stationary state $\nu_1$ and $\nu_2$ and the flavor states $\nu_e$ and $\nu_\mu$, while $\Delta m^2 \equiv m_2^2 - m_1^2$ represents the squared mass difference between $m_1$ and $m_2$. Neutrino oscillations occur if neutrinos are massive particles, if their masses are non degenerate ($m_1 \neq m_2$) and if $\theta \neq 0$. Nature has fulfilled for us all these conditions and neutrino
oscillations are actually observables in many systems: in neutrinos produced from the sun, in neutrinos generated by cosmic ray interactions with the earth atmosphere and, more recently, in artificial neutrinos produced by nuclear reactors and accelerators.

All experimental results gathered so far are mutually consistent if we assume just three active neutrinos - the ones observed in a direct manner in 1956 ($\nu_e$ [3]), 1962 ($\nu_\mu$, [4]), and 2001 ($\nu_\tau$, [5]) - and if we describe such flavor states as superposition of three mass eigenstates labeled $m_1$, $m_2$ and $m_3$, respectively [6]. As for the case of quarks, mass eigenstates and flavor eigenstates do not coincide and the unitary matrix that transform the former to the latter is non-diagonal. In the quark case, this matrix is called the Cabibbo-Kobayashi-Maskawa (CKM [7]) matrix and can be parametrized by three Euler angles $\theta_{12}, \theta_{23}$ and $\theta_{13}$ and one “complex phase” $\delta$ the first angle $\theta_{12}$ being the “Cabibbo angle” $\theta_C$. In the quark sector we know for sure that $\delta$ is different from zero: it causes CP violation in hadrons as observed e.g. in the neutral kaon decays since 1964 [8] or in the neutral B decays since 2001 [9]. For leptons, the corresponding matrix is sometimes referred as the Pontecorvo-Maki-Nakagawa-Sakata ($U_{PMNS}$) mixing matrix [2, 10]. If neutrinos are Dirac particle as the quarks - i.e. neutrinos and antineutrinos are different particles - $U_{PMNS}$ is, again, a $3 \times 3$ unitary matrix and its three angles are the same as for the CKM (three Euler angles bounded between 0 and $\pi/2$ and one complex CP violating phase $\delta$ ranging from 0 to $2\pi$). Two additional complex phases appear if neutrinos are Majorana particles, i.e. if neutrinos and antineutrinos are the same particle; these “Majorana phases” are, however, unobservable in oscillations [1] and will not be considered hereafter. Moreover, $U_{PMNS}$ is not necessarily unitary: in future - and in a way similar to the CKM - direct unitarity tests will likely become an active subject of empirical investigation.

Neutrino oscillations are a powerful tool to determine the squared mass differences of the rest masses of neutrinos and the four parameters $\theta_{12}, \theta_{23}, \theta_{13}$ and $\delta$. The experimental results obtained so far point to two very distinct mass differences, $\Delta m^2_{sol} = \Delta m^2_{12} \equiv m_2^2 - m_1^2 = 7.65^{+0.23}_{-0.26} \times 10^{-5}$ eV$^2$ and $|\Delta m^2_{atm}| = |\Delta m^2_{23}| \equiv |m_3^2 - m_2^2| \simeq |m_3^2 - m_1^2| = 2.40^{+0.12}_{-0.11} \times 10^{-3}$ eV$^2$ [11]. In jargon, $\Delta m^2_{12}$ is called the “solar mass scale” because it drives oscillation of solar neutrinos, but, of course, if the energy of the neutrino and the source-to-detector distance are properly tuned, it can be observed also using man-made neutrinos, e.g. reactor neutrinos located about 100 km from the detector (as it was the case for KAMLAND [12]). Similarly, the standard framework predicts that atmospheric neutrinos mainly oscillate at a frequency that depends on $\Delta m^2_{23}$ (“atmospheric scale”). Accelerator neutrinos can see (actually, saw in K2K [13] and MINOS [14]) the same effect using neutrinos of energy around 1 GeV and source-to-detector distances (“baselines”) of a few hundreds of km (250 km in K2K and 730 km in MINOS). Only two out of the four parameters of the leptonic mixing matrix are known: $\theta_{12} = 33.5^{+1.3}_{-1.0}$ degrees and $\theta_{23} = 42^{+4}_{-3}$ degrees [11]. Surprisingly, these values are much larger than for the CKM ($\theta_{12} \approx 13^\circ$ and $\theta_{23} \approx 23^\circ$). The other two parameters, $\theta_{13}$ and $\delta$, are still unknown: for the mixing angle $\theta_{13}$ direct searches at reactors (the CHOOZ [15] and Palo Verde [16] experiments) combined with solar neutrino data give the upper bound $\theta_{13} \leq 11.5^\circ$ at 90% CL, whereas for the leptonic CP-violating phase $\delta$ we have no information whatsoever. In the standard framework, atmospheric neutrinos mainly oscillate from $\nu_\mu$ to $\nu_\tau$ and vice-versa with the $\Delta m^2_{23}$-driven frequency. All other transitions are sub-dominant and depend on the parameter $\theta_{13}$. The probability of $\nu_\mu \rightarrow \nu_\tau$ transitions at the atmospheric scale is, at leading order, $\simeq 0.5 \sin^2 2\theta_{13} \sin^2 \left[1.27 \Delta m^2_{23} L / E \right]$, so its smallness is a consequence of the smallness of $\theta_{13}$ in $U_{PMNS}$. All these considerations hold in the standard framework, i.e. under the assumption that atmospheric neutrinos disappear due to $\nu_\mu \rightarrow \nu_\tau$ oscillation. This is a well-grounded assumption, which is however being tested in a very straightforward manner (observation of $\nu_\tau$ charged-current interactions) at the CERN-to-Gran Sasso (CNGS) neutrino beam [17].

Reactor antineutrinos are a classical tool to probe the size of $\theta_{13}$ since they have an energy of a few MeV and the ratio $L/E$ matches the atmospheric scale, i.e. $1.27 \Delta m^2_{23} L / E \simeq \pi / 2$, at baselines of about 1 km. If they oscillate toward tau or muon antineutrinos, an apparent flux reduction in the detector will be observed. Currently, the best direct experimental limit on $\theta_{13}$ comes from

\footnote{The parameter $\delta$ is actually a real number that describes the phase factor $e^{i\delta}$ appearing in the mixing matrix.}
the CHOOZ reactor experiment. A world limit can be derived \[18\] by a full 3ν analysis of all the neutrino oscillation experiments, see Tab. 1. Such world limit provides a slightly looser value than the CHOOZ limit. It is an indication that the best fit for θ\(_{13}\) might be different from zero \[19\], although with small statistical significance (< 2σ).

\[
\sin^2 \theta_{13} \leq \begin{cases} 
0.049 (0.072) & \text{(solar + KamLAND)} \\
0.033 (0.051) & \text{(Chooz + atm + K2K + MINOS)} \\
0.032 (0.046) & \text{(global 2008 data)} \\
0.04 (0.05) & \text{(global 2009 data)} 
\end{cases}
\]

| Table 1: The 90% CL (3σ) bounds on sin\(^2\)θ\(_{13}\) from an analysis of different sets of data [18] |

A preliminary analysis of the MINOS experiment \[20\] shows a 1.5σ excess of ν\(_{e}\)-like events in the far detector, that could be interpreted as a manifestation of non-zero value of θ\(_{13}\). Very recently, however, the Super-Kamiokande Collaboration \[21\] presented an updated analysis of its full atmospheric neutrino sample: their data do not support the above hint for θ\(_{13}\) ≠ 0.

A non-zero value of the mixing angle θ\(_{13}\) plays an essential role in neutrino oscillation physics. Since late 90’s, it has been realized that the oscillation ν\(_{μ}\) → ν\(_{e}\) at the atmospheric scale has a very rich structure. Its leading term depends on sin\(^2\)2θ\(_{13}\) but other subdominant terms suppressed by power of the ratio Δ\(_{23}\)/Δ\(_{13}\) contain explicit dependence on the CP phase δ. Moreover, neutrino propagation from the source to the detector through the earth is affected by matter effects similar to the ones perturbing the free streaming of the solar neutrinos \[22\]. It is a remarkable fact that such perturbations are sensitive not only to the overall size of Δ\(_{23}\) but also to its sign, i.e. to the relative ordering of \(m_1, m_2\) and \(m_3\). In the most used parametrization of the leptonic mixing \[23\] \(m_2 > m_1\) by definition and \(m_3\) can be either larger (“normal hierarchy”) or smaller (“inverted hierarchy”) than \(m_2\), giving sign(Δ\(_{23}\)) > 0 and sign(Δ\(_{23}\)) < 0 respectively. Again, this information might be retrieved from high precision experiments measuring both ν\(_{μ}\) → ν\(_{e}\) and ν\(_{μ}\) → ν\(_{τ}\) transitions. The unique role of ν\(_{μ}\) → ν\(_{e}\) and its CP conjugate ν\(_{μ}\) → ν\(_{τ}\) at the atmospheric scale is a consequence of the fact that the ratio Δ\(_{12}\)/Δ\(_{23}\) is not too small (about 1/30) and three-family interference effects are sizable. Hence, subdominant three-family interference amplitudes are observables with neutrinos in analogy to the \(K^0\)–\(\bar{K}^0\) system for quarks. Again, this occurrence is fortunate and purely accidental. Before 2001, several other values, much smaller than Δ\(_{12}\) ∼ 7.9 × 10\(^{-4}\) eV\(^2\) were still experimentally allowed. The demonstration that Δ\(_{12}\) is in the ballpark of 10\(^{-3}\) eV\(^2\) is considered the real inception of the precision era of neutrino physics, since it opened up the possibility to measure the whole of \(U_{PMNS}\) with artificial sources, save, once more, a finite value for θ\(_{13}\).

To give a feeling of the complexity of the task of studying subdominant ν\(_{μ}\) → ν\(_{e}\) transitions we report below the approximate formula that holds when matter effects are not negligible but matter density is constant along the neutrino path. In this case the transition probability ν\(_{e}\) → ν\(_{μ}\) (\(\bar{ν}_e\) → \(\bar{ν}_μ\)) can be written as \[24\]:

\[
P^\pm (ν_e \rightarrow ν_μ) = X_\pm \sin^2 (2θ_{13}) + Y_\pm \cos (θ_{13}) \sin (2θ_{13}) \cos \left(±δ - \frac{Δm^2_{23}L}{4E_ν}\right) + Z,
\]

where ± refers to neutrinos and antineutrinos, respectively and \(a[eV^2] = ±2\sqrt{2}G_F m_ν E_ν = 7.6 \times 10^{-5} ρ[g/cm^3]E_ν[GeV]\) is the electron density in the material crossed by neutrinos. The coefficients of the two equations are: \(X_\pm = \sin^2 (θ_{23}) \left(\frac{Δm^2_{23}}{|a - Δm^2_{23}|}\right)^2 \sin^2 \left(\frac{|a - Δm^2_{23}|L}{4E_ν}\right)\), \(Y_\pm = \sin (2θ_{12}) \sin (2θ_{23}) \left(\frac{Δm^2_{12}}{|a - Δm^2_{23}|}\right) \sin \left(\frac{aL}{4E_ν}\right) \sin \left(\frac{|a - Δm^2_{23}|L}{4E_ν}\right)\), \(Z = \cos^2 (θ_{23}) \sin^2 (2θ_{12}) \left(\frac{Δm^2_{12}}{|a - Δm^2_{23}|}\right)^2 \sin^2 \left(\frac{aL}{4E_ν}\right)\).

The ν\(_{μ}\) → ν\(_{e}\) transitions are driven by the θ\(_{13}\) term which is proportional to sin\(^2\)2θ\(_{13}\) and \(P(ν_μ \rightarrow ν_e)\) could be strongly influenced by the unknown value of δ\(_{CP}\) and sign(Δ\(_{23}\)). Given the complexity of the ν\(_{μ}\) → ν\(_{e}\) transition formula it will be very difficult for pioneering experiments to extract all the unknown parameters unambiguously. Correlations are present
between $\theta_{13}$ and $\delta$ [24]. Moreover, in absence of information about the sign of $\Delta m^2_{23}$ [25, 26] and the approximate $[\theta_{23}, \pi/2 - \theta_{23}]$ symmetry for the atmospheric angle [27], additional clone solutions rise up. In general, the measurement of $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ will result in eight allowed regions of the parameter space, the so-called eightfold-degeneracy [26]. It can be solved only combining several measurements at different energies or baseline, or exploiting channels different from $\nu_\mu \to \nu_e$, as $\nu_e \to \nu_\tau$.

This is the reason why it is commonly believed that the next generation of experiments will mainly focus on the very evidence of $\nu_e$ appearance at the atmospheric scale, while the task of precision measurement, including CP violation and determination of the mass hierarchy, will take a further round of facilities [28, 29]. At present, there is only one accelerator experiment in data taking - actually in the startup phase - that has been optimized for the search of non-null $\theta_{13}$. It is the T2K [30] experiment in Japan, which is expected to improve by an order of magnitude the limit from CHOOZ exploiting a new beam from JPARC to the pre-existing far detector of SuperKamiokande (Fig. 1). The relevance of $\theta_{13}$ search to ground the future of the field is such that it boosted a large number of proposals to improve CHOOZ with novel detectors at reactors. Among the $\sim 10$ original proposals, three of them survived and are either in commissioning or in construction phase. The most advanced is Double-Chooz [31], in the original CHOOZ site in France, which makes use of a larger far detector and of a new near detector identical to the far detector for flux normalization (a near detector was not available at the time of CHOOZ). Double-Chooz will start data taking in a few months with the far detector only; the near detector will be available after 2011. The other reactor experiments under construction are Daya-Bay [32] in China and RENO [33] in Korea. In particular, the basic experimental layout of Daya Bay consists of three underground experimental halls, one far and two near, linked by horizontal tunnels. Each near hall will host two 20 t gadolinium doped liquid scintillator detectors, while the far hall will host four such detectors. It is the most aggressive layout to push systematics below 0.4%. Other experiments currently in data taking exhibit some sensitivity to $\theta_{13}$. They are MINOS, whose measurement has already been mentioned and OPERA [34] at the Gran Sasso Laboratories (LNGS) of the Italian Institute for Nuclear Research (INFN). In the original plans MINOS was supposed to improve by a factor of two the limit of CHOOZ. However, considering the achieved precision and the fact that MINOS has swapped to antineutrinos, it is unlikely that it will be able to improve significantly the current CHOOZ limit. Also OPERA, which exploits the above-mentioned CNGS beam, is expected to improve the CHOOZ limit [35], although with a timescale that is not competitive with T2K. On the other hand, in the occurrence of large $\theta_{13}$ (see below) the measurement from CNGS would be of great value, being affected by very different systematics with respect to T2K and Double-Chooz.

The observation of the extraordinarily large neutrino mixings when compared to naive Cabibbo-like expectations from quarks, the possibility of Majorana-like couplings and the extraordinary small mass spectrum indicate that neutrinos might have unique features with respect to other elementary fermions. This is why non-standard scenarios have been deeply investigated in literatures, often fostered by experimental anomalies as the one of LSND that dates back to 1995 [35] or, more recently, the “low energy anomaly” of MiniBooNE [36]. Perspectives outside the standard three-family framework are discussed in Sec 4.

**Guessing the Future**

It is of great practical interest to consider the expected sensitivities of accelerator and reactor experiments in the near future. It is, clearly, a quite approximate exercise since most of these experiments are not in regular data taking and therefore, delays or re-scheduling might be possible. This holds particularly for T2K, whose startup will be at very low power (0.1 MW) compared with the design one of 0.75 MW and a progressive ramp-up is foreseen.

Fig. 2 [37] shows the evolution of the $\theta_{13}$ sensitivities as a function of time gathering all the information we have presently in our disposal. Even with such caveat, from the plot one can

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2They do not include the considerations on the final MINOS sensitivity stated above.
Figure 1: The T2K experiment exploits a new neutrino beam of 0.75 MW maximum power built into the JPARC acceleration complex, at the Tokai campus of the Japan Atomic Energy Agency. Neutrinos of mean energy of 0.7 GeV are sent toward the 13-year-old SuperKamiokande detector (22000 ton fiducial mass), located 292 km far from JPARC.
Figure 2: Evolution of experimental $\sin^2 2\theta_{13}$ sensitivities as function of time. All the sensitivities are taken from the proposals of the experiments. For T2K it is assumed a beam power of 0.1 MW the first year, 0.75 MW from the third year and a linear transition in between. NOνA sensitivity is computed for $6.5 \times 10^{20}$ protons-on-target per year and 15000 ton detector mass. Accelerator experiments sensitivities are computed for $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$, $\delta = 0$ and normal hierarchy for all the experiments. The sensitivity curves are drawn starting after six months of data taking. From [37].
Figure 3: Evolution of experimental $\sin^2 2\theta_{13}$ sensitivities of T2K and the reactor experiments Double-Chooz and Daya Bay as function of time, under the same assumptions of Fig. 2. The T2K sensitivity is computed with the Globes code and shown as a band of values evaluated ranging $\delta$ from 0 to $2\pi$ and assuming both normal (NH) and inverted (IH) hierarchy. From [37].

Easily derive that in the next 5 years or so the $\theta_{13}$ parameter will be probed with a sensitivity about 25 times better than the present limit. The figure includes also the startup of NOVA, a new facility in the US based on the existing NuMI beam from Fermilab to Minnesota and its upgrade (see Sec. 2). In fact, the $\theta_{13}$ sensitivity of T2K depends on the unknown $\delta$ parameter and on the mass hierarchy, i.e. $\text{sign}(\Delta m_{23}^2)$; a more detailed comparison of the time evolution of the T2K and reactors sensitivities has to take into account that T2K will actually provide a band of excluded values of $\theta_{13}$ and not just a single point. This is shown in Fig. 3 [37].

From the plot some considerations can be taken:

- The Double-Chooz reactor experiment is very competitive in the first years of operation, when, however, the information coming from its near detector will likely not be available.

- T2K will be dominating our knowledge of $\theta_{13}$ for long time and the evolution of its beam power is the most critical issue in the extrapolation of Fig. 2. It is impossible to state now how the the JPARC neutrino beam line evolves and when it reaches the top value of 0.75 MW, since the facility is based on an entirely new accelerator complex. Therefore, the sensitivity shown here is no more than an educated guess.

- Scheduling is critical for Daya Bay, too. The achievement of tiny systematic errors claimed by the experiment will likely be the most relevant issue to be clarified.

This discussion is based on the limits that can be achieved by each experiment. In case of $\theta_{13}$ in the reach of those experiments, their information will be truly complementary to measure the actual value of the parameter: for a discussion under this hypothesis see [28, 41].
2 A new generation of facilities for the physics of neutrino oscillations

As already mentioned, there is consensus \[28\] on the fact that none of currently running facilities - including the experiments in startup phase as T2K, Double-Chooz or Daya-Bay - will be able to extract all missing parameters of the $U_{PMNS}$ even in the most optimistic case of $\theta_{13}$ close to current limits. On the other hand, what has prompted a rather heated debate is the definition of a “minimal” facility that might be able to address the challenge of extracting such parameters by a detailed study of subdominant transitions at the atmospheric scale. Defining the “optimal facility” without knowing - at least approximately - the size of $\theta_{13}$ is a hopeless exercise but several non-trivial considerations can be done assuming (or excluding) that an evidence of subdominant $\nu_\mu \rightarrow \nu_e$ transitions is within the reach of T2K. Such considerations have also driven important R&D efforts toward novel sources of neutrinos in the GeV range and, correspondingly, toward new detectors for their observation at the far location.

The technologies for neutrino sources that are considered promising for the next generation of facilities can be grouped in three main streams \[42\] called, in jargon, “Superbeams”, “Beta Beams” and “Neutrino Factories” \[43\]. Coordinated R&D efforts have been made around the world to raise these technologies to their adulthood but it is clear that a positive result in the quest of $\theta_{13}$ within the next 2-5 years will prompt a tremendous boost toward their realization. The status of the art on the eve of the T2K run is summarized below, with special emphasis to their implementation in the European framework of infrastructures.

2.1 High Intensity neutrino beams from $\pi$ decays: the Superbeams

Since the 1962 experiment of Lederman et al. \[4\], accelerator neutrinos in the GeV ballpark have only been produced from the decay in flight of pions. This 40-year old technology \[46\] has progressed together with high intensity proton accelerators and, in the last decade, allowed for the construction of long-baseline $\nu_\mu$ beams to explore the leading $\nu_\mu \rightarrow \nu_\tau$ transition at the atmospheric scale (Fig. 4). Long baseline experiments have also been possible thanks to the large size of the atmospheric mixing ($\sin^2 2\theta_{23} \simeq 1$), which partially compensates the loss in intensity due to the large source-detector distance. At CERN, it allowed for the re-use of the SPS, formerly employed for short-baseline experiments at the WANF (CHORUS \[44\] and NOMAD \[45\]) to feed a 17 GeV beam from CERN to Gran Sasso.

Moving from leading to subleading oscillations ($\nu_\mu \rightarrow \nu_e$ transitions), the bonus of the large mixing angle disappears ($\theta_{13} \ll \theta_{23}$) and the intensity is no more sufficient to explore these transitions at a level better than CHOOZ. Such considerations hold also for other long-baseline beams in the world that played a role in the current round of experiments, as the already mentioned NuMI beam from Fermilab to Minnesota and the K2K beam from KEK to SuperKamiokande (see Fig. 4). In Japan, it would have been impossible to re-use the very low intensity K2K beam in this new phase. As a result, the construction of a new facility has been pursued since 2003, leveraging the enormous investment (about 1 Billion €) made for JPARC and aimed to a much broader community than neutrino physicists. It brought the T2K project into existence without the need of building either a dedicated proton accelerator or a new far detector: the former leverages the 50 GeV general purpose synchrotron of JPARC complemented by a dedicated neutrino beamline, the latter the existing SuperKamiokande detector; although the additional investment for the neutrino beamline was demanding (about 200 M$), it comes to no surprise that the T2K project is by far the most advanced among the experiments conceived to improve the current limits of $\theta_{13}$. Its running schedule has already been discussed in Sec. 1.

Both US and Europe have neutrino facilities much more powerful than the K2K beamline. The NuMI beam might be operated up to 0.4 MW, i.e. at 40% of the maximum power achievable by T2K. Unfortunately, there is no far detector in the US that can exploit such power since MINOS is too dense to perform precision measurements of $\nu_e$ appearance. The construction of a dedicated 15 kton detector (NOVA \[39\]), started on May 2009 and located 810 km from Fermilab (see...
Figure 4: The long baseline experiments run to gather evidence for neutrino oscillations and measure the leading parameters at the atmospheric scale ($\Delta m^2_{23}$ and $\theta_{23}$). The KEK-to-Kamioka (K2K) experiment in Japan from KEK to SuperKamiokande (250 km) operated from 1999 to 2004; the MINOS experiment located 730 km far from Fermilab along the NuMI neutrino beam (still running); the OPERA and ICARUS detectors located at the Gran Sasso laboratories and detecting neutrinos from CNGS beam (still running).
Fig. 5 brings the timeline of the first physics results a few years after T2K and without significant improvements on the knowledge of $\theta_{13}$ but with some marginal sensitivity to the mass hierarchy due to the large baseline (810 versus 292 km). However, the existence of NOVA together with a positive result from T2K could ground a second generation facility, based on a new neutrino beam fed by a 2 MW, 8 GeV, proton accelerator (“Project X” [47]). In fact, as a part of the NOVA project, Fermilab plans an upgrade of NuMI based on the exploitation of the Fermilab “Recycler Ring” after the shut-down of the Tevatron. The Recycler Ring will be used as a pre-injector of the Fermilab “Main Injector” reducing the cycle time (Fig. 6). It needs, however, the construction of a dedicated transfer line and the upgrade of the radio-frequency system in both the Recycler and the Main Injector. This upgrade [48] could finally bring NuMI to an peak power comparable to T2K: 0.7 MW and $6 \times 10^{20}$ protons-on-target per year (pot/y) at 120 GeV.

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. 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 [50] 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 (Fig. 7). 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 ($3.3 \times 10^{20}$ NOVA pot/y). At a longer timescale (>2016), the replacement of the PS with a new 50 GeV synchrotron (PS2 [51]) 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). It is, therefore, a situation that closely resembles the one of the NuMI upgrade but unfortunately, its realization cannot be anticipated before 2017 due to the priority to the

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To ease comparison with NOVA and following [49], we suggest, as a rule of thumb, to scale the integrated pot with the linear ratio of the primary proton energy. Hence, a nominal CNGS year corresponds to $1.5 \times 10^{20}$ “NOVA” pot/y.
running of the LHC and the corresponding funding limitations from CERN for the construction of the new injectors. At that timescale, it would be more interesting to consider a high-flier option, specifically suited for the exploration of CP violation and the mass hierarchy in case of positive result from T2K - along the line of the US “Project X”. The rationale of this approach is that a multi-MW proton source can, in principle, serve for a variety of needs and feed a rich physics programme ranging from neutrino physics to muon and kaon physics and to physics with radioactive ion beams [52, 53]. This option has been considered at CERN in the framework of the construction of a pre-injector for PS2: the Superconducting Proton Linac (SPL). The pre-injector, feeding PS2 with 2-4 GeV protons, has been conceived in year 2000 as a 2.2 GeV accelerator for a future neutrino factory based at CERN and its design was based on the recycling of the radio-frequencies formerly employed at LEP [54]. Over the time, the design has been updated and currently points toward a 3.5-4 GeV, 4 MW system with dedicated equipment based on bulk Niobium cavities [55]. This proton energy might feed a Superbeam producing neutrinos at a rather low energy (about 300 MeV) that could be exploited by a very massive detector located not far from CERN (CERN-to-Frejus [56]).

The technology of the Superbeam is considered the most straightforward way to explore leptonic mixing in case of positive result from T2K and/or Double-Chooz and, therefore, it is viewed as a solid option in Japan (Tokai to HyperKamiokande - see below) and US (Fermilab/Project X to DUSEL) [57]. Unfortunately, it also shows evident limitations:

- It is not a “pure” source of neutrinos of a given flavor, being plagued by the $\nu_e$ 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 $\nu_e$ contamination will likely be the main limitation for a precise determination of CP violation in the leptonic sector [58];

- It produces mainly $\nu_\mu$ and, therefore, the leptonic mixing is studied through $\nu_\mu \to \nu_e$ and its CP conjugate $\bar{\nu}_\mu \to \bar{\nu}_e$, i.e. looking for electrons in the final state instead of muons. It thus requires huge, low density detectors to be hosted in underground sites (see below);

- in a Superbeam, CP violation appears as an asymmetry between the probability of transition $\nu_\mu \to \nu_e$ and its CP conjugate $\bar{\nu}_\mu \to \bar{\nu}_e$. At low proton energies, the production yield of $\pi^-$ is suppressed with respect to $\pi^+$. This suppression, together with the suppression due to the cross section ($\sigma_\nu/\sigma_\bar{\nu} \simeq 1/2$), makes the antineutrino run much more time-consuming that the neutrino run.
Figure 7: The CERN accelerator complex, which includes the Proton Synchrotron (PS), the Super-Proton-Synchrotron (SPS), the Large Hadron Collider (LHC) and the CERN Neutrino beam to Gran Sasso (CNGS).
A multi-MW proton accelerator and the corresponding neutrino beamline is considered feasible in less than a decade [59] but it requires a substantial effort in accelerators and targetry, a major resource investment (of the order of 500 M€) and feedback from the operation of neutrino facilities in the sub-MW range (firstly T2K).

Far Detectors for the Superbeams

Most of the information gathered at the atmospheric scale on leptonic mixing come from the study of muon neutrino disappearance in natural (atmospheric) and artificial (accelerator) sources. The use of Superbeam forces experimentalists to build detectors that are specifically designed for the identification of electron neutrinos. $\nu_e$ appearance is extremely challenging compared with $\nu_\mu$ disappearance because prompt electromagnetic showers must be distinguished from neutral-currents events where electromagnetic showers occur through the production of $\pi^0$. A low density, high granularity target is mandatory to allow showers to develop and to perform a precise kinematic reconstruction in order to separate effectively neutral-current (NC) from charged-current (CC) events. Unfortunately, only a few of the techniques currently applied for electromagnetic calorimetry can be scaled to a size suitable for neutrino oscillation physics (at least tens of ktons). Actually, due to the current constraints to the size of $\theta_{13}$, it is believed that even in the occurrence of a clear evidence for $\nu_\mu \rightarrow \nu_e$ oscillations at T2K, the size of the detectors should be upgraded by nearly an order of magnitude with respect to the current generation of experiments. Thanks to the experience of SuperKamiokande, Japan maintains a leadership in Water Cherenkov detectors and the proposal of building a new very massive detector of about 500 kton fiducial mass is considered the most plausible upgrade of T2K (the “megaton-size” Hyper-Kamiokande detector [60]), possibly complemented with a second detector in Korea [61]. Similar options are considered in US for the new DUSEL underground laboratory in South Dakota, and in Europe for a possible major extension of the Frejus Labs. The only two other viable technologies that are considered scalable to such size [62, 63] are the ones of the Liquid Argon detectors and of liquid/plastic scintillators. C. Rubbia proposed the use of liquid Argon Time Projection Chambers (LAr TPC) since 1977 [64] and INFN maintains a world leadership in the LAr technology thanks to the results of the ICARUS Collaboration that built such detectors up to a size of 600 tons [65]. Due to its finer granularity and superior quality in reconstructing and identifying particles and rejecting NC events, LAr can achieve sensitivities to $\nu_e$ appearance comparable or better than SuperKamiokande with smaller masses (in the 10 kton range). To catch up with the megaton-size Water Cherenkov detectors, LAr TPC’s should reach fiducial volumes of about 100 kton: an extrapolation of about two order of magnitudes with respect to the T600, which necessarily requires a very intensive R&D. This phase might be substantially reduced following a modular approach, where the 10-20 kton initial mass can be successively enlarged as needed.

Synergies with non-accelerator astroparticle physics

Bringing liquid detectors to this immense size requires experimental halls that do not exist in any part of the world. If the technology of Superbeams is chosen as a reference for the post-T2K phase, the Gran Sasso Laboratories will not be able to host any far detector. In this framework, an intermediate size (20 kton) detector in Italy could only be hosted by a new shallow-depth laboratory, as proposed in [49]. On the other hand, large liquid detectors with a fiducial mass significantly bigger than SuperKamiokande come with a bonus of a physics programme much broader than neutrino oscillations and, therefore, are at the focus of important R&D programmes worldwide. If located underground or - at least for LAr - even at a relatively shallow depths (~ 500 m.w.e. [66]), they could improve significantly the current measurements on proton decay, supernovae, solar and atmospheric neutrinos and, hence, they would represent a major step forward in experimental astroparticle physics.

In 2007 the European Union has approved a Design Study (LAGUNA [67]) aimed at evaluating extensions of the present deep underground laboratories in Europe (Boulby, Canfranc and Frejus)
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 $e^+\nu_e\bar{\nu}_\mu$). However, realistic layouts to get intense neutrino sources have become available only in recent times [71]. 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 [72] 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 ($\nu_\mu \to \nu_e$). Since $\mu^\pm$ decay into $e^\pm\nu_e\bar{\nu}_\mu$, it is possible to investigate $\nu_e \to \nu_\mu$ oscillations seeking for the appearance of $\mu^-$ from $\nu_\mu$ CC events (“wrong sign muons”), provided that we are able to separate these events from the bulk of $\mu^+$ (“right sign muons”) coming from unoscillated $\bar{\nu}_\mu$. A. De Rujula et al. [73] underlined that the simultaneous exploitation of $\mu^-$ and $\mu^+$ decays would be an ideal tool to address CP violation in the leptonic sector, with outstanding performance compared with pion-based sources. The only condition to be fulfilled was a large ratio $\Delta m^2_{12}/\Delta m^2_{23}$ (see Sec. 1) and, of course, the finite size of $\theta_{13}$. The results from KAMLAND and SNO [74] confirming $\Delta m^2_{12}/\Delta m^2_{23} \simeq 1/30$ boosted enormously Geer’s proposal, together with the above-mentioned proposals for Superbeams. Moreover, Geer’s ideas 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. Actually, motivations were so strong that the early ideas of building the Neutrino Factory (NF) as a front-end of the muon collider have been dropped and current designs are all optimized for neutrino physics. It mainly implied a relaxation of the ultra-challenging constraints on muon cooling needed for the construction of the collider [75]. In spite of this, 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 [76]: in Europe this programme is especially fostered by UK. Among the NF-oriented projects we recall MICE [77] at the Rutherford Appleton Laboratories (ionization cooling), HARP [78] at CERN (hadroproduction for the front-end proton accelerator), MERIT [79] at CERN (targetetry), EMMA [80] at Daresbury (fixed-field alternating-gradient accelerators) and the MUCOOL R&D [81] at Fermilab (radio-frequency 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 50 GeV, although more realistic scenarios suggest decay rates in the ballpark of $2 - 5 \times 10^{20}$ decay/y and with energies in the 20-50 GeV range (corresponding to neutrinos in the 10-30 GeV range) [82]. After the work of the International Scoping Study (ISS) [43] [57] [63], 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 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 $\nu_\mu$ 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. In jargon, this issue is dubbed the “degeneracy problem” and it has already been mentioned in Sec. [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 $\nu_e \rightarrow \nu_\tau$ at baseline around 1000 km (“silver channel”) [3] (see below). The exploitation of the silver channel, moreover, is useful to investigate the occurrence of non-standard interactions in the neutrino sector [34]. 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 (∼ 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.

Far Detectors for the Neutrino Factories

At the Neutrino Factory, experimentalists search for the appearance of multi-GeV $\nu_\mu$, a signal with a very clear topology even in high-density, low granularity detectors. As a result, the baseline technology for NF far detectors are magnetized iron calorimeters with masses of the order of several tens of ktons, although other low-density options have also been investigated. Magnetized iron calorimetry is a classic technique in neutrino physics, brought to the multi-kton size by the MINOS Collaboration. Similar techniques based on Resistive Plate Chambers instead of plastic scintillators have been proposed in the past (MONOLITH [85]) for a second generation atmospheric neutrino experiment in the Hall C of LNGS - the same Hall that presently hosts OPERA and Borexino [80] - and, more recently, in a new underground lab close to Bangalore in India (INO [87]). They have been proposed to measure the sinusoidal pattern of the neutrino oscillations with multi-GeV $\nu_\mu$ and $\overline{\nu}_\mu$ produced in the earth atmosphere, improve the knowledge of the leading atmospheric parameters $\theta_{23}$ and $\Delta m^2_{23}$ and, at least for large values of $\theta_{13}$ (> 5° [88]), determine the sign of $\Delta m^2_{23}$ through matter effects. The main challenge with respect to MINOS is represented by the compelling request on the muon charge identification (≪ 10⁻³ of misidentification probability) in order to suppress the bulk of “right sign muons”. Current R&D are focused on the optimization of the granularity and on the technology choice for the active detector to achieve optimal charge identification and pion rejection at the lowest possible visible energy [89]. Clearly, Hall C of LNGS is an ideal place to host a 30-40 kton detector[4]. A Neutrino Factory based at the Rutherford Labs (RAL), along the line pursued by UK, could be suited for a LNGS far-detector, although the RAL-LNGS distance is about 1500 km (i.e. a factor of two smaller than the optimal one suggested by the ISS). In the context of a CERN-based NF, LNGS is too close for an optimal sensitivity to CP violation or mass hierarchy. On the other hand, the LNGS location is interesting to study the “silver channel” ($\nu_e \rightarrow \nu_\tau$). The silver channel represents a unique opportunity to exploit technologies mastered within INFN [90]: the appearance of the $\nu_\tau$ can be observed by nuclear emulsion based detectors in a way similar to the one currently employed by OPERA at CNGS. In the Neutrino Factory framework, the detectors should be suited for the identification of the tau lepton, provided that they are able to measure the wrong-sign muons. An OPERA-like

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4The peak of the oscillation occurs (see Eq[1]) when $1.27 \Delta m^2_{23} L/E = \pi/2$. This situation holds also at CNGS, where OPERA and ICARUS are located at 730 km but the neutrino energy cannot be lowered below O(10) GeV to stay beyond the kinematic threshold for tau production. In this case, the oscillation peak is at $1.27 \cdot 2.5 \times 10^{-3} (\text{eV}^2) \cdot 730 \; \text{(km)} \cdot 2/\pi = 1.5 \; \text{GeV}$. Similarly, at a Neutrino Factory with a detector located 3000 km far from the source, the peak is at 6 GeV.

5In the original MONOLITH proposal, a 30 kton detector had to be installed next to Borexino, in the area presently filled by the OPERA detector. A significantly larger mass could be achieved in future.
2.3 Neutrinos from radioactive ion decays: the Betabeam

The enormous progress in the technology of Radioactive Ion Beams has led P. Zucchelli \cite{91} to the proposal of a neutrino facility based on the decay in flight of $\beta$-unstable ions (for a full review see \cite{92}). Unlike the NF, these “Betabeams” (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. 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 $\nu_\mu$ 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 NF. The original proposal of \cite{91} 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 Betabeam triggered the interest of nuclear physics community, which was offered a stimulating synergy with the neutrino programme at CERN. As a result, such proposal \cite{56,93} was studied in a systematic manner within the framework of the EURISOL Design Study\cite{7} (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, 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, few MeV, proton accelerators, which are quite similar to the linacs that have to be built for the International Fusion Materials Irradiation Facility \cite{94}. 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. From the point of view of the physics performance, an additional weakness stems from the fact that the SPS is able to accelerate these ions up to relatively low energies, so that the corresponding emitted neutrinos are just in the sub-GeV range. This impacts on the choice of the detectors (see below) and on the cross sections, which are highly depleted.

To improve the performance of the Eurisol Beta Beam several alternatives to the SPS have been considered: a high energy SPS (“SuperSPS” \cite{95}) accelerating protons up to 1 TeV (a machine originally envisaged for the energy and luminosity upgrade of the LHC) or even the LHC itself \cite{96,97}. 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 $\gamma$ 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. \cite{99} 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 Betabeam. 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 will be at focus in the framework of the EURO$\nu$ Design Study\cite{100} 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. Although the BB optimization is a complex task [101, 102, 103], some simple scaling laws can be used as reference. For a given number of decays per year $N_\beta$, if we label with $\gamma$ the Lorentz factor of the ion (which depends on the machine employed to accelerate the ion), with $Q$ the Q-value of the isotope and with $L$ the source-detector distance, the events at the far location are proportional to the convolution of the flux ($\phi \sim \gamma^2 / L^2$), of the cross section ($\sigma \sim E_\nu \sim Q \gamma$) and of the oscillation probability, times $N_\beta$. If the facility is operated at the maximum of the oscillation probability, then $1.27 \Delta m^2 L / E_\nu = \pi / 2$; therefore, $L \sim Q \gamma$. As a result the number of events are proportional to $N_\beta \gamma / Q$. Note, however, that also $N_\beta$ has a dependence on $\gamma^{-1}$ due to the increase of the ion lifetime in the lab frame at larger $\gamma$.

Summarizing, a high-Q BB needs a smaller $\gamma$ for the same neutrino energy, with the advantage that an accelerator of larger energy than the SPS would not be needed and that the length of the decay ring could be shortened. On the other hand, given the Beta Beam kinematics, for the same baseline $L$ an high-Q BB needs an order of magnitude more ions at the source to match the performance of a high-$\gamma$ BB.

In general, the clarification of the issue of the ion production yield is considered a crucial milestone for the Betabeam. 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.

Detectors and experimental challenges for the Betabeams

A far detector within a BB facility seeks for the appearance of $\nu_\mu$ (or $\bar{\nu}_\mu$) during the run with $^6$He and $^9$Li in a bulk of unoscillated $\nu_e$. Therefore, their detection can be even simpler than for the NF, charge identification being immaterial in this case. In the SPS-based BB option, the energy of the outcoming neutrinos lays in the sub-GeV range. Here, the range of the muons is comparable with the one of the pions and high density detectors cannot perform a clear NC/CC separation. Atmospheric neutrinos in such range are typically studied with water Cherenkov detectors or with LAr TPC’s. Therefore, the ideal technology for such “low-energy” BB turns out to be identical to the ideal technology for the Superbeams. Moreover, even for nominal ion fluxes, the smallness of the cross section requires very large detector masses, again in the range of the Superbeam far detectors (e.g. the above-mentioned Hyper-Kamiokande detector). Clearly, with respect to a Superbeam, the BB offers a nearly complete control of the source systematics at the expenses of a riskier technology and larger costs. Unlike the NF, atmospheric neutrinos are a significant background since - lowering the energy - its cross-section weighted rate increases roughly as $E^{-1.7}$. Suppression of atmospheric $\nu_\mu$ requires the exploitation of time-correlation between the ion bunch injected in the decay ring and the time of detection at the far location. In turn, bunches shorter than 100 ns are needed, which also represent an accelerator challenge. Betabeams producing neutrinos in the multi-GeV range (Advanced Beta Beams) would open, once more, the possibility of employing high density detectors and offer LNGS the opportunity to host a BB far detector. This option (iron calorimeter in Hall C) has been addressed explicitly in [97] for a SuperSPS BB with $^{18}$Ne and $^6$He. It is less appealing than for the above-mentioned case of the NF: the somewhat limited mass cannot compensate for the lower event rate of the BB with respect to the NF. Moreover, the neutrino energy is still quite small (about 1.5 GeV) and, therefore, the neutral-current contamination is significant. Larger neutrino energies (e.g. from $^8$Li and $^8$B) could further enhance its physics case, although the CERN-LNGS baseline would not be any more at the oscillation maximum. If the ion yield were appropriate, a natural solution - of noteworthy strategic interest for INFN and CERN - would be the use of the SPS with $^8$Li and $^8$B pointing to an iron calorimeter located at LNGS. Physics performance are expected to be

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.
comparable with the ones of \[97\].

3 Future scenarios in the standard oscillation framework

Depending on the value of \(\theta_{13}\), the experimental approach toward a full measurement of the \(U_{PMNS}\) will be substantially different. We discuss below three different ranges of \(\theta_{13}\) values: very large values, those suggested at 90\% CL by the global fits of Fogli et al. \[19\] and experimentally accessible in a couple of years, large values, corresponding to the ultimate sensitivity of the next generation of dedicated experiments, say T2K and Daya Bay, accessible in 5-7 years, and small values of \(\theta_{13}\), i.e. smaller than the combined sensitivity of the next experiments.

To discriminate among the options, we use as a reference the sensitivity plots computed within the aforementioned (see Sec. 2.2) International Scoping Study (ISS) \[57\]. Figs. 8,9,10 display the expected sensitivity of the facilities discussed in Sec. 2 - Super Beams, Beta Beams and Neutrino Factories - in measuring \(\theta_{13}\), sign(\(\Delta m^2_{23}\)) and \(\delta\) as a function of \(\theta_{13}\). Since the performance of the facilities have large uncertainties, they are displayed as wide areas under different assumptions on the final layout and on the limiting systematics\(^8\). Note that in some cases, the width of the area can be even larger than one order of magnitude. It is worth stressing that so far no realistic estimate of costs and timescales of Neutrino Factories and Beta Beams exists: it is one of the prime tasks of the European Network EURO\(\nu\) (see Footnote 7) to reach firm conclusions on this item.

3.1 Very large \(\theta_{13}\) (\(\theta_{13} \geq 8^\circ\) or \(\sin^2 2\theta_{13} \geq 0.08\))

If \(\theta_{13}\) is just below the CHOOZ limit, it will be measured in the first runs of T2K and Double-Chooz, hopefully within 2010. For so large \(\theta_{13}\), first results on leptonic CP violation might be reached by upgrading the beam intensity of the existing facilities (T2K and NO\(\nu\)A) with no new gigantic far detectors \[28\]. It is easily predictable that such upgrades will have a very high priority in Japan and USA and in the meantime a megaton water Cerenkov detector (or 100 kton liquid Argon detectors) could likely be funded at Kamioka and/or DUSEL.

In such a scenario a major investment in Europe for a new infrastructure would be fully justified. In Italy, it might bring to the construction of a new shallow-depth laboratory to host LAr TPC’s of a size not accessible at LNGS. This option has been discussed in the framework of the ModulAr proposal \[49\], where a 20 kton detector would be installed slightly off the main axis of CNGS, in a way that resembles the location of NOVA along the Fermilab-to-Minnesota neutrino beam (see Fig.5). In general, the use of the imaging capability of the LAr-TPC ensures a higher discovery potential than in the case of scintillator (or water) detectors, i.e. a comparable sensitivity may be achieved with a smaller sensitive mass.

From the point of view of LNGS, large values of \(\theta_{13}\) will bring measurable signals in OPERA. The OPERA result would be very interesting: it is truly complementary to the T2K and NOVA results since the facility is operated off the peak of the oscillation maximum and with completely different systematics \[38, 104\]. As a consequence it would be very recommendable a prolongation of the OPERA run, possibly with an intensity upgrade of the CNGS.

3.2 Medium values of \(\theta_{13}\) (\(\theta_{13} \geq 2^\circ\) or \(\sin^2 2\theta_{13} \geq 0.005\))

In this range of values a non-zero \(\theta_{13}\) value will be established at 3\(\sigma\) in the full run of T2K and Daya Bay (around 2015). For these values no simple upgrades of T2K and NOVA will have sensitivity on CP violation and mass hierarchy (we include ModulAr in this class of experiments), and detectors of the class of Hyper-Kamiokande will be needed. This is a favorable scenario for the Superbeams: they represent a relatively low risk technology and can get a clearly accessible physics case for medium values of \(\theta_{13}\). In Europe the SPL project, with a megaton class detector

\(^8\)For details, we refer the reader to the first volume of the full ISS report \[57\]. A comprehensive description of the detector options and accelerator performance are available in Vol. II \[63\] and Vol. III \[43\], respectively.
Figure 8: The capability to demonstrate that $\theta_{13} \neq 0$ at $3\sigma$ level for different facilities. The discovery limits are shown as a function of the fraction of all possible values of the true value of the CP phase $\delta$ (‘Fraction of $\delta_{CP}$’) and the true value of $\sin^2 2\theta_{13}$. The right-hand edges of the bands correspond to more conservative setups while the left-hand edges correspond to fully optimized setups. The discovery reach of the SPL super beam from CERN to Frejus is shown as the orange band, that of Hyper-Kamiokande (T2HK) as the yellow band, and that of Fermilab to DUSEL “wide band” beam [88] 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 [57].
Figure 9: The capability to distinguish between normal and inverted mass hierarchy at 3 \( \sigma \) level for different facilities. The discovery limits are shown as a function of the fraction of all possible values of the true value of the CP phase \( \delta \) (‘Fraction of \( \delta_{\text{CP}} \)’) 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 [57].
Figure 10: The capability to establish CP violation in the leptonic sector at 3 σ level for different facilities. 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 δCP') and the true value of \( \sin^22\theta_{13} \). 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 [57].
installed in a new cavern at the Frejus Laboratories, could compete with these projects, having a better sensitivity on $\theta_{13}$ and CP violation and a worse sensitivity on mass hierarchy \[56\]. In this race, Europe suffers from some disadvantages. It is likely that only one megaton-size detector will be funded world-wide. Japan is a leader on this technology and US would likely exploit the discovery of $\theta_{13}$ to boost this opportunity at DUSEL. Moreover, at that time (2016) CERN will be engaged with the replacement of the PS and, probably, with the luminosity upgrades of the LHC, so funding for an ultimate facility for astroparticle physics might be difficult to be gathered to successfully face a competition with US and Japan.

As noted above, however, Europe could pursue better suited strategies than the standard Superbeam. If the feasibility of a high-Q SPS-based Betabeam can be demonstrated in a few years from now, CERN could potentially host a novel facility for neutrino oscillations exploiting either smaller detectors (high density calorimeters in Hall C) or with significantly better performance if combined with a 100 kton size LAr TPC. According to \[103\], in this range of values the optimal facility (the one that could measure $\theta_{13}$, sign($\Delta m_{23}^2$) and $\delta$ with just one detector) would be a high-$\gamma$ (or even an SPS based) Beta Beam pointing to a megaton water Čerenkov detector or a detector with equivalent performance (e.g. a 100 kton LAr TPC).

There is however a more conservative approach that might be extremely interesting for UK and Italy. The guarantee of the physics case due to the finite size of $\theta_{13}$ can be used to strongly boost the realization of a Neutrino Factory based at the Rutherford Labs. As a consequence, CP violation and matter effect could be studied in the experimental halls of LNGS building a iron magnetized detector (see Sec. 2.2) located about 1500 km from the source. Ultimate precision for $\theta_{13}$ and for the resolution of the degeneracies will be achieved exploiting the second RAL-to-India baseline (7000 km).

### 3.3 Small values of $\theta_{13}$ ($\theta_{13} \leq 3^\circ$ or $\sin^2 2\theta_{13} \leq 0.01$, i.e. null results from the next generation of experiments)

If no signal of $\theta_{13}$ will be detected by the next generation of accelerator and reactor experiments, a rather problematic scenario will disclose.

The discovery potential of Super Beam experiments like Hyper-Kamiokande and DUSEL would be quite limited (they have $3\sigma$ CP violation sensitivity for $\theta_{13}$ values as small as about $\sin^2 2\theta_{13} \leq 0.005$) and it seems very unlikely that those facilities will be built under these circumstances. Advanced Beta Beams and Neutrino Factories can explore $\theta_{13}$ values two or three orders of magnitude smaller than the T2K sensitivity, but again it seems unlikely that facilities of such cost will be strongly supported having as a physics case just the exploration of the $\theta_{13}$ value and a search for CP violation without any guaranteed signal. On the other hand it seems unlikely that neutrino oscillation experiments stop without mapping the values of three fundamental parameters of the Standard Model: $\theta_{13}$, sign($\Delta m_{23}^2$) and $\delta$, also considering that in the framework of Leptogenesis $\delta$ is the single most important unknown ingredient to address matter-antimatter asymmetry in the Universe \[105\]. In this case, however, any progress in oscillation neutrino physics will rely on advances in Beta Beams, Neutrino Factory or further novel sources.

### 4 Neutrino oscillation physics beyond the standard framework

Among elementary fermions, neutrinos have a unique status due to charge neutrality and the extremely small value of their mass. Most likely, they are the only Majorana particles up to the electroweak scale and, differently from other oscillating particles, their coherence length can extend up to cosmic scales \[106\]. It comes to no surprise that these particle have been speculated to have unusual properties. Within several models, their free streaming in vacuum and matter is perturbed by non-standard interactions, which can be constrained mainly by oscillation experiments. Even Lorenz-invariance and CPT conservation \[107\] have been challenged for neutrinos. As a matter
of fact none of these hypotheses are empirically grounded and the constraints coming from the oscillation experiments and from cosmology are extremely tight. However, a further stimulus to pursue these searches has come from the persistent LSND anomaly, which mainly brought to the consideration of additional sterile neutrinos.

LSND indicated a $\nu_\mu \rightarrow \nu_e$ oscillation with a third, very distinct, neutrino mass difference: $\Delta m_{LSND}^2 \sim 0.3 - 6 \text{ eV}^2$ [115]. Already in 1999, Fogli et al. [108] showed that the standard three neutrino framework is inconsistent with the ensemble of all experimental data, included LSND. To explain the whole set of data at least four different light neutrino species would have been needed (referred as “3+1” models).

Sterile neutrinos are particles with the same quantum number of the vacuum and, therefore, are “sterile” with respect to electroweak interactions. In the standard three-family framework, massive sterile neutrinos are the ordinary right-handed components of the Dirac fermions and they do not mix with active neutrinos. Beyond this model, light steriles could mix with active $\nu$ and, therefore, change the transition probability through a $N \times N$ leptonic mixing matrix with $N > 3$ [109]. These model predicted of course several other oscillation processes in excess to the $\nu_\mu \rightarrow \nu_e$ transitions detected by LSND, the largest part already excluded by other short baseline experiments. As a consequence, these 3+1 models provided anyway poor overall fits to the existing experimental data [110].

The MiniBooNE experiment at FermiLab was designed to directly check the LSND claim, performing a search for $\nu_\mu \rightarrow \nu_e$ appearance with a baseline of 540 m and a mean neutrino energy of about 700 MeV, i.e. with energy and baseline larger than LSND but with the same ratio $L/E$. In 2007 MiniBooNE published a no-evidence analysis for $\nu_\mu \rightarrow \nu_e$ oscillation [111]. While this analysis was not able to rule-out the whole parameter space of the LSND signal [112], it represented a further suppression of the four-neutrino interpretation of the LSND anomaly. In 2009 MiniBooNE [113] published also results for $\nu_\mu \rightarrow \nu_e$ oscillation showing, again, no appearance effects, although at a smaller significance with respect to the neutrino data.

MiniBooNE neutrino data reported also an unexplained excess for low energy neutrinos (MiniBooNE anomaly in the following), that cannot be reconciled with any sterile model. This data excess was not present in the antineutrino run. At present, electron (anti)neutrino appearance results, including the LSND and the MiniBooNE anomalies, can be reconciled in a “3+2” model [114]. However results from muon neutrino disappearance experiments at short baselines are in disagreement with this model [112] [114] so that the world dataset are clearly inconsistent with both 3+1 and 3+2 model predictions and even more baroque models should be advocated.

It is interesting to analyze whether the CNGS might be able to test the LSND anomaly, in spite of the much larger $L/E$. Naively, if the LSND anomaly comes from a two family oscillation source of $\nu_\mu \rightarrow \nu_e$ parametrized as $\sin^2 2\theta_{LSND} \cdot \sin^2 (\Delta m_{LSND}^2 L/4E)$ with $\Delta m_{LSND}^2 \simeq 1 \text{ eV}^2$ [116] at CNGS the probability of $\nu_\mu \rightarrow \nu_e$ oscillation would be very high (i.e. $0.5 \sin^2 2\theta_{LSND}$) since the oscillating term averages out to 1/2. Moreover, thanks to the increase of the cross section at 17 GeV, the CNGS would perform significantly better than MINOS or other long-baseline experiments. Unfortunately, if any realistic model (e.g. 3+1) is used to compute the actual rate at LNGS, the effect is rather small, since models must evade the already stringent bounds from atmospheric neutrinos. A detailed calculation of the performance of the CNGS to test the LSND anomaly has been done in [116]. In general, we can expect that the CNGS will improve marginally the bounds on the sterile parameters and, surprisingly, much more from the $\nu_\mu \rightarrow \nu_\tau$ analysis than from the $\nu_\mu \rightarrow \nu_e$. On the other hand, $\nu_\mu \rightarrow \nu_\tau$ oscillations are particularly suited to test unconstrained parameters for the non-standard interactions. It has been shown, for instance, that operators affecting the $\nu_\mu \rightarrow \nu_\tau$ transitions and compatible with current constraints from

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9The LSND experiment indeed wasn’t able to define the range of $\Delta m^2$; what is quoted here is the region not completely excluded by other experiments.

10This formula would be plausible for instance if you did not need two different mass scales to explain the solar and atmospheric neutrinos: in this case $\Delta m_{LSND}^2$ could play the role of $\Delta m_{12}^2$ or $\Delta m_{23}^2$. Although oversimplified, this formula is still used to express the sensitivity coverage of KARMEN [115] and MiniBooNE with respect to the LSND claim.
atmospheric might change substantially the number of observed tau events in OPERA [117]. It is, however, in the framework of the neutrino factories that a superior test of non-standard interactions (at 1-0.1 % level) can be carried out either with or without a detector for the silver channel [118].

Given the present experimental situation, the most straightforward way to test (again) LSND is to perform a similar experiment at the same L and E but with significantly larger statistics. An experiment based on large fluxes of pions decaying at rest and in flight has been recently proposed at the new US neutron spallation source (SNS) [119].

Another straightforward way would be to incorporate a close detector in the MiniBooNE setup, greatly reducing the impact of systematic errors in the experimental analysis. The recent BooNE letter of intents [120] showed that building a second MiniBooNE detector at (or moving the existing MiniBooNE detector to) a distance of \( \sim 200 \) m from the Booster Neutrino Beam (BNB) production target, the sensitivity of the setup would result greatly enhanced.

Similarly, the MiniBooNE low-energy anomaly - which is located at a different E and L/E with respect to LSND - might be studied directly using a high granularity detector positioned along the same beam of MiniBooNE (BooNE beamline) at Fermilab (“MicroBooNE” [121]). This detector, operated both at BooNE and at NuMI could simultaneously test the above-mentioned anomaly and perform high precision cross section measurement in the critical region around 1 GeV. This region is of great practical interest since most of the Superbeams proposed so far are operated in such energy range; it is explored by a dedicated cross-section experiment called SciBooNE [122] and, along NuMI, by Minerva [123]. The LAr technology is ideal to perform these measurements and, therefore, it has been proposed as the basic technology option for MicroBooNE up to mass of 170 t (70 t fiducial mass).

As discussed in [124, 125], an even larger detector of 500 t active mass could be built at CERN restoring the low-energy neutrino beamline driven by the PS and originally used for BEBC-PS180 [126]. The detector would be positioned 850 m far from the source and complemented by a smaller near detector at 127 m (150 t active mass). An identical setup, with the notable difference of a totally active scintillator detector instead of liquid argon, was proposed to CERN already in 1997 [127]. With respect to MicroBooNE, the presence of an identical near detector strengthen significantly the reliability of the oscillation search and the overall mass allows for a test based on a much larger statistics. On the other hand, this setup requires the construction of a dedicated beamline and proper sharing of the protons of the PS, which also feed the rest of the CERN physics programme (SPS fixed target and the LHC). The CERN option (1.1 GeV at 850 m) works, once more, at the same L/E as LSND. The values of L and E, however, are different both with respect to the original LSND apparatus and also with respect to MiniBooNE (0.7 GeV at 550 m). This situation is ideal if the source of anomaly has the usual L/E pattern but could be non optimal if the LSND and/or the MiniBooNE excess has a different origin.

## 5 Conclusions

In this paper, we investigated the perspectives for accelerator neutrino physics in Europe, with special emphasis to the line of research where INFN infrastructures (firstly LNGS) and expertise could be most profitably exploited. If all further data coming from the current and next generation of experiments fit the standard oscillation framework, i.e. the assumption of three active neutrinos with Standard Model couplings, then the strategy for the next decade will be solely driven by the actual size of \( \theta_{13} \). In particular:

- if \( \theta_{13} \) is close to the current limits (> 8°) and therefore can be observed very early by T2K or Double-Chooz, an independent measurement done in parallel by the CNGS experiments would be of high value: it could be obtained by high granularity detectors with completely different systematics with respect to T2K and, moreover, running off the peak of the oscillation probability, with no dependence on matter effect and with a dependence of the cosine of the CP phase instead of the usual \( \sin \delta \) term. Therefore, a prolongation of the
CNGS, possibly running in dedicated mode or profiting from an intensity upgrade should definitely be pursued. Moreover, in this special case medium size detectors (T2K, NOVA) with upgraded beams could play a relevant role for precision measurement in the leptonic sector. A medium size (20 kton) LAr detector - having performance comparable or better than NOVA - could complement the T2K measurements, especially with the aim of determining the mass hierarchy of neutrinos through the observation of matter effects. Clearly, it is an ideal scenario for CERN and INFN, who would fully profit of the investments done for CNGS even beyond the primary aim of the experiment, i.e. the observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations.

- for lower values of $\theta_{13}$, several options can be envisaged both inside and outside the Gran Sasso Laboratories. In a timescale shorter than the Neutrino Factory, a SPS-based Betabeam at CERN accelerating high-Q ions might become available. In this case, an experimental hall of the Gran Sasso labs would be enough to host a high density detector (e.g. iron calorimeter) operating in $\nu_\mu$ appearance mode. A high-Q Betabeam requires a significant R&D which, however, is synergical with the activities of nuclear physics community and it surely exploits in a clever manner European infrastructures, as CERN, the INFN Laboratories of Legnaro, CRC at Louvain and several other labs working on the development of radioactive ion beams.

On the other hand, in this range of $\theta_{13}$, the construction of the Neutrino Factory is considered as the ultimate and most precise facility for the study of lepton mixing. LNGS could host the far detector of a UK-based Neutrino Factory although the distance from the Rutherford Labs to LNGS is shorter than the optimal one (1500 versus 3000 km). This option offers the best physics performance at a price of a longer timescale since it is unrealistic that a Neutrino Factory comes into operation before 2020.

In the context of a CERN-based or RAL-based Neutrino Factory (>2020), an option highly synergical with INFN infrastructures and technologies is the study of $\nu_e \rightarrow \nu_\tau$ transitions at LNGS using detectors able to identify the appearance of tau leptons, as it was the case of the CNGS. This “silver channel” can be exploited at LNGS by a $\sim$5 kton OPERA-like or ICARUS-like detector equipped by a magnetic spectrometer for $\mu$ charge measurement and detecting neutrinos from CERN or RAL. This channel can be used to solve the degeneracies in the mixing parameters when measured with an ultimate facility as the Neutrino Factory itself.

Without Betabeams or Neutrino Factories, there is no way to use the halls of LNGS profitably over this range of $\theta_{13}$. As an alternative (or in parallel, if resources and interest from other countries can be gathered), the European neutrino community could pursue an aggressive R&D to boost the LAr technology to the 100 kton size: an ultimate facility for astroparticle physics and for the technology of the Superbeam.

- in case of no evidence of $\nu_e$ appearance after T2K, it is unlikely that accelerator neutrino physics will gather major investments. R&D toward the Neutrino Factory will proceed at a lower rate and will be done synergically with a possible Muon Collider while a megaton-size Water Cherenkov detector or a 100 kton LAr TPC will be mainly motivated by astroparticle physics and proton decay searches.

Outside the standard framework, we still see some opportunities especially for “low” mass Liquid Argon detectors in the quest for the clarification of the low energy excess of MiniBooNE. The most natural application is in the framework of MicroBooNE [121]: an experiment based on a $\sim$ 100 ton LAr TPC and located at Fermilab, along the BooNE and NuMI beamline. Alternatively, as pointed out in [124], the PS neutrino beamline at CERN could be restored to perform a similar test with better significance, and with the added value of the continuity in the development and exploitation of the LAr technology within Europe. Note, however, that in a few year a further test [119] of the original LSND anomaly might also be done at the SNS, the US high intensity neutron source already in operation at the Oak Ridge National Labs.
As a final consideration, we wish to stress that these years - which have witnessed the completion and the startup of the CNGS and, more recently, of Double-Chooz - are unique times to look to the future of neutrino physics with artificial sources in Europe [29]. Clearly, the optimal strategy will be finally driven by the outcomes of the $\theta_{13}$-oriented experiments, but a systematic exploration of the different alternatives as a function of these outcomes was missing in literature, especially when focusing to the existing European infrastructures and to technologies where INFN has a world leadership: we hope that this paper fills such gap at best of our present knowledge of lepton mixing.

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References

[1] See C. Giunti, C.W. Kim, “Fundamentals of Neutrino Physics and Astrophysics”, Oxford University Press, 2007, and references therein.

[2] B. Pontecorvo, Sov. Phys. JETP 6 (1957) 429 [Zh. Eksp. Teor. Fiz. 33 (1957) 549]; B. Pontecorvo, Sov. Phys. JETP 6 (1968) 984 [Zh. Eksp. Teor. Fiz. 53 (1967) 1717].

[3] C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse and A. D. McGuire, Science 124 (1956) 103.

[4] G. Danby, J. M. Gaillard, K. Goulianos, L. M. Lederman, N. B. Mistry, M. Schwartz and J. Steinberger, Phys. Rev. Lett. 9 (1962) 36. For early proposals of accelerator neutrino experiments see also M. A. Markov “Early development of weak interactions in the USSR” Nauka Publisher, Central Depart. of Oriental Literature, Moscow (1985) and B. Pontecorvo, Sov. Phys. JETP 10 (1960) 1236 [Zh. Eksp. Teor. Fiz., 37 (1959) 1751].

[5] K. Kodama et al. [DONUT Collaboration], Phys. Lett. B 504 (2001) 218.

[6] For a discussion of neutrino masses and the information that can be drawn from neutrino oscillations see e.g. A. Bettini, Riv. Nuovo Cimento 32 (2009) 295.

[7] N. Cabibbo, Phys. Rev. Lett. 10 (1963) 531; M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.

[8] J. H. Christenson et al., Phys. Rev. Lett. 13 (1964) 138.

[9] B. Aubert et al., Phys. Rev. Lett. 87 (2001) 091801; K. Abe et al., Phys. Rev. Lett. 87 (2001) 091802.

[10] Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28 (1962) 870; Y. Katayama, K. Matumoto, S. Tanaka and E. Yamada, Progr. Theor. Phys. 28 (1962) 675; B. Pontecorvo, Sov. Phys. JETP 26 (1968) 984 [Zh. Eksp. Teor. Fiz. 53 (1967) 1717]; V. N. Gribov and B. Pontecorvo, Phys. Lett. B 28 (1969) 493.

[11] T. Schwetz, M. A. Tortola and J. W. F. Valle, New J. Phys. 10 (2008) 113011.

[12] S. Abe et al. [KamLAND Collaboration], Phys. Rev. Lett. 100 (2008) 221803.
[13] M. H. Ahn et al. [K2K Collaboration], Phys. Rev. D 74 (2006) 072003.
[14] P. Adamson et al. [MINOS Collaboration], Phys. Rev. Lett. 101 (2008) 131802.
[15] M. Apollonio et al. [CHOOZ Collaboration], Eur. Phys. J. C 27 (2003) 331.
[16] F. Boehm et al., Phys. Rev. D 64 (2001) 112001.
[17] G. Acquistapace et al., CERN-YELLOW-98-02 (1998); R. Baldy et al., INFN-AE-99-5 (1999).
[18] T. Schwetz, M. Tortola and J. W. F. Valle, New J. Phys. 10 (2008) 113011.
[19] A. B. Balantekin and D. Yilmaz, J. Phys. G 35 (2008) 075007; G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A. M. Rotunno, Phys. Rev. Lett. 101 (2008) 141801; M. Maltoni and T. Schwetz, arXiv:0812.3161 [hep-ph].
[20] M. V. Diwan, “Recent Results from the MINOS experiment,”, proceedings of “Thirteen International Workshop on Neutrino Telescopes”, Venezia, March 10-13, 2009, arXiv:0904.3706 [hep-ex].
[21] T. Kajita and R. Wendell, Talks at the 11th International Conference on Topics in Astroparticle and Underground Physics (TAUP2009), Rome, 1-5 Jul 2009.
[22] L. Wolfenstein, Phys. Rev. D 17 (1978) 2369; S. P. Mikheev and A. Y. Smirnov, Sov. J. Nucl. Phys. 42 (1985) 913 [Yad. Fiz. 42 (1985) 1441].
[23] C. Amsler et al. [Particle Data Group], Phys. Lett. B667 (2008) 1.
[24] J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez and O. Mena, Nucl. Phys. B 608 (2001) 301.
[25] H. Minakata and H. Nunokawa, JHEP 0110 (2001) 001.
[26] V. Barger, D. Marfatia and K. Whisnant, Phys. Rev. D 65 (2002) 073023.
[27] G. L. Fogli and E. Lisi, Phys. Rev. D 54 (1996) 3667.
[28] For a recent update see P. Huber, M. Lindner, T. Schwetz and W. Winter, arXiv:0907.1896 [hep-ph].
[29] Current and future facilities in Europe and perspectives in US and Japan have been discussed in the “European Strategy for Future Neutrino Physics” Workshop, CERN, 1-3 October 2009. Information are available at http://indico.cern.ch/conferenceDisplay.py?confId=59378.
[30] Y. Itow et al. [The T2K Collaboration], arXiv:hep-ex/0106019.
[31] F. Ardellier et al. [Double Chooz Collaboration], arXiv:hep-ex/0606025.
[32] X. Guo et al. [Daya-Bay Collaboration], arXiv:hep-ex/0701029.
[33] S. B. Kim [RENO Collaboration], AIP Conf. Proc. 981 (2008) 205 [J. Phys. Conf. Ser. 120 (2008) 052025].
[34] M. Guler et al. [OPERA Collaboration], CERN-SPSC-2000-028, CERN-SPSC-P-318, LNGS-P25-00, 2000;
R. Acquafredda et al. [OPERA Collaboration], New J. Phys. 8 (2006) 303;
R. Acquafredda et al. [OPERA Collaboration], JINST 4 (2009) P04018.
C. Athanassopoulos et al. [LSND Collaboration], Phys. Rev. Lett. 75 (1995) 2650; C. Athanassopoulos et al. [LSND Collaboration], Phys. Rev. C 54 (1996) 2685; C. Athanassopoulos et al. [LSND Collaboration], Phys. Rev. C 58 (1998) 2489; A. Aguilar et al. [LSND Collaboration], Phys. Rev. D 64 (2001) 112007.

A. A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. Lett. 102 (2009) 101802.

M. Mezzetto, “Next Challenge in Neutrino Physics: the theta(13) Angle,” proceedings of “Thirteen International Workshop on Neutrino Telescopes”, Venezia, March 10-13, 2009, arXiv:0905.2842 [hep-ph].

M. Komatsu, P. Migliozzi and F. Terranova, J. Phys. G 29 (2003) 443.

D. S. Ayres et al. [NOvA Collaboration], arXiv:hep-ex/0503053. See also http://www-nova.fnal.gov.

P. Huber, M. Lindner and W. Winter, Comput. Phys. Commun. 167 (2005) 195; P. Huber, J. Kopp, M. Lindner, M. Rolinc and W. Winter, Comput. Phys. Commun. 177, 432 (2007).

P. Huber, M. Lindner, M. Rolinc, T. Schwetz and W. Winter, Nucl. Phys. Proc. Suppl. 145 (2005) 190.

Other venues have also been explored: they include the exploitation of Mossbauer neutrinos (R. S. Raghavan, arXiv:hep-ph/0601079; H. Minakata, H. Nunokawa, S. J. Parke and R. Zukanovich Funchal, Phys. Rev. D 76 (2007) 053004), high intensity radioactive sources (Y. Giomataris and J. D. Vergados, Nucl. Instrum. Meth. A 530 (2004) 330) and laser-driven sources (S. V. Bulanov, T. Esirkepov, P. Migliozzi, F. Pegoraro, T. Tajima and F. Terranova, Nucl. Instrum. Meth. A 540 (2005) 25).

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

E. Eskut et al. [CHORUS Collaboration], Nucl. Instrum. Meth. A 401 (1997), 7; E. Eskut et al. [CHORUS Collaboration], Nucl. Phys. B 793 (2008) 326.

P. Astier et al. [NOMAD Collaboration], Phys. Lett. B 570, 19 (2003); J. Altegoer et al. [NOMAD Collaboration], Nucl. Instrum. Meth. A 404, 96 (1998).

S. E. Kopp, Phys. Rept. 439 (2007) 101.

Information and documentation available at http://projectx.fnal.gov/

D.S. Ayres et al., “The NOVA (E929) Technical Design Report”, public Draft Version available online at http://www-nova.fnal.gov/nova_cd2_review/tdr/tdr.htm

B. Balbussinov et al., Astropart. Phys. 29 (2008) 174.

M. Meddahi and E. Shaposhnikova, CERN-AB-2007-013.

Information available at http://paf-ps2.web.cern.ch/paf-ps2/

D. Bettoni et al., Phys. Rept. 434 (2006) 47.

W. Marciano, talk at the 2nd Workshop on Physics with an Intense Proton Source, Fermilab, IL, Jan 25-28 2008. Available at www.fnal.gov/directorate/Longrange/Steering_Public/workshop-physics-2nd.html

B. Autin et al., “Conceptual design of the SPL, a high-power superconducting H- linac at CERN,” CERN-2000-012.
[55] M. Baylac et al., “Conceptual design of the SPL II : A high-power superconducting H- linac at CERN”, CERN-2006-006. O. Brunner et al., Phys. Rev. ST Accel. Beams 12 (2009) 070402.

[56] J. E. Campagne, M. Maltoni, M. Mezzetto and T. Schwetz, JHEP 0704 (2007) 003.

[57] A. Bandyopadhyay et al. [ISS Physics Working Group], arXiv:0710.4947 [hep-ph].

[58] P. Huber, M. Mezzetto and T. Schwetz, JHEP 0803 (2008) 021.

[59] J. Hylen, talk at 11th International Workshop on Neutrino Factories, Superbeams and Beta Beams (Nufact09), Chicago, IL, July 20-25, 2009.

[60] M. Koshiba, Phys. Rep. 220 (1992) 229; K. Nakamura, Talk at Int. Workshop on Next Generation Nucleon Decay and Neutrino Detector, 1999, SUNY at Stony Brook; K. Nakamura, Neutrino Oscillations and Their Origin, (Universal Academy Press, Tokyo, 2000), p. 359.

[61] T. Kajita and K. Soo-Bong (eds.), Proceedings of the 3rd International Workshop On a Far Detector In Korea For The J-PARC Neutrino Beam 30 Sep - 1 Oct 2007, Tokyo, Japan.

[62] D. Antierco et al., JCAP 0711 (2007) 011.

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

[64] C. Rubbia, “The liquid Argon Time Projection Chamber: a new concept for Neutrino Detector, CERN-EP/77-08.

[65] S. Amerio et al. [ICARUS Collaboration], Nucl. Instrum. Meth. A 527 (2004) 329.

[66] A. Bueno et al., JHEP 0704 (2007) 041

[67] L. Oberauer, Nucl. Phys. Proc. Suppl. 188 (2009) 321.

[68] L. Mosca, AIP Conference Proceedings 944 (2007) 65.

[69] L. Oberauer, F. von Feilitzsch and W. Potzel, Nucl. Phys. B (Proc. Suppl.) 138 (2005) 108; T. Marrodan Undagoitia et al., J. Phys. Conf. Ser. 120 (2008) 052018; J. Peltoniemi, arXiv:0911.4876 [hep-ex]; J. Peltoniemi, arXiv:0911.5234 [hep-ph].

[70] A. Rubbia, J. Phys. Conf. Ser. 171 (2009) 012020.

[71] S. Geer, Lecture at the 1st International Neutrino Factory Summer Institute, Abingdom, UK, June 24-29, 2002.

[72] S. Geer, Phys. Rev. D 57 (1998) 6989 [Erratum-ibid. D 59 (1999) 039903].

[73] A. De Rujula, M. B. Gavela and P. Hernandez, Nucl. Phys. B 547 (1999) 21.

[74] Q. R. Ahmad et al. [SNO Collaboration], Phys. Rev. Lett. 87 (2001) 071301.

[75] A. Blondel, talk at 11th International Workshop on Neutrino Factories, Superbeams and Beta Beams (Nufact09), Chicago, IL, July 20-25, 2009.

[76] A. Bross, “The Neutrino Factory: The Final Frontier in Neutrino Physics?” FERMILAB-CONF-09-169-APC, Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.

[77] G. Gregoire et al. [MICE Collaboration] “MICE: International Muon Ionisation Cooling Experiment, Technical Reference Document.”, MICE-TRD-2005 (2005).

[78] M.G. Catanesi et al., [HARP Collaboration] “Proposal to study hadron production for the neutrino factory and for the atmospheric neutrino flux”, CERN-SPSC/99-35 (1999).
[79] H.G. Kirk et al., “The MERIT High-Power Target Experiment at the CERN PS”, EPAC08-WEPP169, FERMILAB-CONF-08-224-APC, presented at the European Particle Accelerator Conference (EPAC 08), Genova, Italy, 23-27 Jun 2008.

[80] R. Edgecock et al., “EMMA - the World’s First Non-scaling FFAG”, EPAC08-THPP004 (2008), presented at the European Particle Accelerator Conference (EPAC 08), Genova, Italy, 23-27 Jun 2008.

[81] J. Norem et al. “The MUCCOL RF Program.”, FERMILAB-CONF-06-387-AD, JLAB-ACC-06-481; presented at the European Particle Accelerator Conference (EPAC 06), Edinburgh, Scotland, 26-30 Jun 2006.

[82] S. Geer and M. S. Zisman, Prog. Part. Nucl. Phys. 59 (2007) 631.

[83] A. Donini, D. Meloni and P. Migliozzi, Nucl. Phys. B 646 (2002) 321. D. Autiero et al., Eur. Phys. J. C 33 (2004) 243.

[84] J. Kopp, T. Ota and W. Winter, Phys. Rev. D 78 (2008) 053007.

[85] N. Agafonova et al., “MONOLITH: A massive magnetized iron detector for neutrino oscillation studies.”, LNGS-P26-2000, CERN-SPSC-2000-031; F. Terranova et al., Int. J. Mod. Phys. A 16S1B (2001) 736.

[86] G. Alimonti [Borexino Collaboration] et al., Nucl. Instrum. Meth. A 600 (2009) 568.

[87] M. Sajjat Athar et al., “India-based neutrino observatory”, INO-2006-01, available at http://www.imsc.res.in/ino/; V. M. Datar et al., J. Phys. Conf. Ser. 136 (2008) 022016.

[88] A. Samanta, Phys. Lett. B 673 (2009) 37.

[89] A. Cervera-Villanueva, “ISS/IDS detector study,” AIP Conf. Proc. 981 (2008) 51.

[90] The “Emulsion Cloud Chamber” detector concept dates back to 1956 [J. Nishimura, Soryusiron Kenkyu, Japan 12 (1956) 24]. In the 80’s, this technology has been revived by the progress in automatic scanning techniques achieved in Japan [S. Aoki, et al., Nuclear Tracks 12 (1986) 249; S. Aoki, et al., Nucl. Instr. and Meth. B 51 (1990) 466] and applied in large size experiments as DONUT [5], CHORUS [44] and OPERA [34].

[91] P. Zucchelli, Phys. Lett. B 532 (2002) 166.

[92] M. Lindroos and M. Mezzetto, “Artificial Neutrino Beams: Beta Beams”, Imperial College Press, Aug. 2009.

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

[94] M. Martone et al., “International Fusion Materials Irradiation Facility Conceptual Design Activity”, RT/ERG/FUS/96-11.

[95] O. Bruning et al., “LHC luminosity and energy upgrade: A feasibility study,” CERN-LHC-PROJECT-REPORT-626.

[96] J. Burguet-Castell, D. Casper, J. J. Gomez-Cadenas, P. Hernandez and F. Sanchez, Nucl. Phys. B 695 (2004) 217; F. Terranova, A. Marotta, P. Migliozzi and M. Spinetti, Eur. Phys. J. C 38 (2004) 69; S. K. Agarwalla, A. Raychaudhuri and A. Samanta, Phys. Lett. B 629 (2005) 33.

[97] A. Donini, E. Fernandez-Martinez, P. Migliozzi, S. Rigolin, L. Scotto Lavina, T. Tabarelli de Fatis and F. Terranova, Eur. Phys. J. C 48 (2006) 787; A. Donini et al., Eur. Phys. J. C 53 (2008) 599.
[124] C. Rubbia, “DOUBLE-LAr: sterile neutrinos at the CERN-PS?”, Talk at the Workshop on “New Opportunities in the Physics Landscape at CERN”, CERN, 10-13 May 2009.

[125] B. Baibussinov et al., arXiv:0909.0355 [hep-ex].

[126] C. Angelini et al. [PS180 Coll.], Phys. Lett. B 179 (1986) 307.

[127] N. Armenise et al., “Letter of Intent: Search for $\nu_\mu \rightarrow \nu_e$ oscillation at the CERN PS”, CERN-SPSC/97-21, SPSC/1216 (1997); M. Guler et al., “Proposal: Search for $\nu_\mu \rightarrow \nu_e$ oscillation at the CERN PS”, CERN-SPSC/99-26, SPSC/P311 (1999).