Measurement of three-family neutrino mixing and search for CP violation

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Abstract

The measurements of the parameters of the neutrino mixing matrix in the present and future neutrino oscillation experiments at accelerators are presented. The perspectives for high intensity new neutrino facilities as SuperBeams, BetaBeams and Neutrino Factories devoted to precise measurements subleading numu to nue oscillation parameters at the atmospheric scale are discussed. Emphasis is on the determination of the currently unknown 1-3 sector of the leptonic mixing matrix (i.e. the mixing between the first and third generation and the CP violating Dirac phase) and on possible experimental programs to be developed in Europe.

1 Neutrino oscillations

The experimental evidences for neutrino oscillations collected in the last six years represent a major discovery in modern particle physics. The oscillation phenomenon allows the measurement of fundamental parameters of the Standard Model and provides the first insight beyond the electroweak scale [1]. Moreover, they are important for many fields of astrophysics and cosmology and open the possibility to study CP violation in the leptonic sector.

Neutrino flavor oscillations can be described in term of three mass eigenstates \( \nu_1, \nu_2, \nu_3 \) with mass values \( m_1, m_2 \) and \( m_3 \) that are connected to the flavor eigenstates \( \nu_e, \nu_\mu \) and \( \nu_\tau \) by a mixing matrix \( U \), usually parameterized as

\[
U(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}) = \begin{pmatrix}
  c_{13}c_{12} & c_{13}s_{12} e^{i\delta_{CP}} & s_{13} e^{-i\delta_{CP}} \\
-s_{13}c_{12} - s_{13}s_{23}c_{12} e^{i\delta_{CP}} & c_{23}c_{12} - s_{13}s_{23}s_{12} e^{i\delta_{CP}} & s_{13}c_{23} s_{12} e^{i\delta_{CP}} \\
  s_{23}s_{12} - s_{13}s_{23}c_{12} e^{i\delta_{CP}} & -s_{23}c_{12} - s_{13}c_{23}s_{12} e^{i\delta_{CP}} & c_{13}c_{23}
\end{pmatrix}
\]

(1)

where the short-form notation \( s_{ij} \equiv \sin \theta_{ij}, c_{ij} \equiv \cos \theta_{ij} \) is used. As a result, the neutrino oscillation probability depends on 3 mixing angles, \( \theta_{12}, \theta_{23}, \theta_{13} \), 2 mass differences, \( \Delta m^2_{21} = m_2^2 - m_1^2 \), \( \Delta m^2_{32} = m_3^2 - m_2^2 \), and a CP phase \( \delta_{CP} \). Additional phases are present in case neutrinos are Majorana particles, but they do not influence at all neutrino flavor oscillations. Furthermore, the neutrino mass hierarchy, the ordering with which mass eigenstates are coupled to flavor eigenstates, can be fixed by measuring the sign of \( \Delta m^2_{23} \). In vacuum the oscillation probability between two neutrino flavors \( \alpha, \beta \) is:

\[
P(\nu_\alpha \to \nu_\beta) = \frac{-4}{\sum_{k>j}} \text{Re}[W^j_{\alpha j}] \sin^2 \frac{\Delta m^2_{j k} L}{4E_\nu} \pm 2 \sum_{k>j} \text{Im}[W^j_{\alpha j}] \sin^2 \frac{\Delta m^2_{j k} L}{2E_\nu}
\]

(2)

where \( \alpha = e, \mu, \tau, j = 1, 2, 3, W^j_{\alpha \beta} = U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k} \). In the case of only two neutrino flavor oscillation it can be written as:

\[
P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \Delta m^2(eV^2) \cdot L(km)}{E_\nu(GeV)}.
\]

(3)
Three claims of neutrino flavor oscillations come from atmospheric neutrinos, solar neutrinos and beam dump experiments.

A clear evidence of $\nu_\mu$ disappearance of atmospheric neutrinos, through a strong zenithal modulation and an anomalous value of the ratio of electron to muon neutrino events is reported by the Super-Kamiokande experiment[4], a result well supported by Soudan2[5] and Macro[6] experiments. Furthermore, Super-Kamiokande reported an oscillation signature by directly measuring the $L/E_\nu$ parameter[7] and detected an indirect evidence of $\nu_\tau$ appearance ruling out at 99% C.L. possible pure oscillations into sterile neutrinos[8]. It follows that the most likely channel is an almost pure $\nu_\mu \rightarrow \nu_\tau$ transition, connected with the $m_2$ and $m_3$ mass eigenstates, central values are $|\Delta m_{23}^2| = 2.1 \cdot 10^{-3}$ eV$^2$, $\sin^2 2\theta_{23} = 1$ and at 90% C.L. $1.5 \cdot 10^{-3}$ eV$^2 < |\Delta m_{23}^2| < 3.4 \cdot 10^{-3}$ eV$^2$, $\sin^2 2\theta_{23} > 0.92$[9]. Mechanisms other than neutrino oscillations, as neutrino decay or decoherence[10], are almost completely ruled out by the experimental data.

The long-baseline experiment K2K published evidence for $\nu_\mu$ disappearance in a neutrino beam with a mean energy $\langle E_\nu \rangle \simeq 1.2$ GeV sent to the Super-Kamiokande detector at a baseline of 250 km[11]. The experimental result: $\sin^2 2\theta_{23} = 1.0$, 1.9 $\cdot 10^{-3} < |\Delta m_{23}^2| < 3.6 \cdot 10^{-3}$ eV$^2$ at 90% C.L., is in agreement with the atmospheric data.

Solar neutrino evidence for oscillations comes from the counting deficit of four experiments which took data at different thresholds: Homestake[12], Gallex-GNO[13], Sage[14] and Super-Kamiokande[15]. The latter experiment also measured the energy shape distortions and day-night effects[16]. The spectacular comparison of the charged current, elastic scattering and neutral current rates in the SNO experiment[17] allowed convincing evidence of $\nu_\mu$, $\nu_\tau$ appearance and a first precise determination of the oscillation parameters.

The reactor experiment KamLAND, running at the solar $\Delta m^2$ scale, reported evidence for $\bar{\nu}_e$ disappearance[15] in perfect agreement with the solar data.

A combined analysis of solar plus reactor data shows that the most likely channel is a transition of $\nu_e$ into other active flavors ($\nu_\mu$ and $\nu_\tau$) whose oscillation probability is modulated by $\Delta m_{12}^2$, central values are $|\Delta m_{12}^2| = 7.9_{-0.6}^{+0.7} \cdot 10^{-5}$ eV$^2$, $\tan^2 \theta_{12} = 0.40_{-0.07}^{+0.10}$[19].

A further indication of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with a $\Delta m^2$ of 0.3–20 eV$^2$ comes from the beam dump LSND experiment detecting a 4$\sigma$ excess of $\bar{\nu}_e$ interactions in a neutrino beam produced by $\pi^+$ decays at rest where the $\bar{\nu}_e$ component is highly suppressed ($\sim 7.8 \cdot 10^{-4}$)[20]. The KARMEN experiment[21], with a similar technique but with a lower sensitivity (a factor 10 less for the lower $\Delta m^2$), and the NOMAD experiment at WANF of CERN SPS[22] (for $\Delta m^2 > 10$ eV$^2$) do not confirm the result, excluding a large part of the allowed region of the oscillation parameters. The LSND result doesn’t fit the overall picture of neutrino oscillations and several non-standard explanations, as for instance sterile neutrinos, have been put forward to solve this experimental conflict. The MiniBooNE experiment at FNAL, presently taking data, is designed to settle this puzzle with a 5$\sigma$ sensitivity[23].

The $\theta_{13}$ mixing angle represents the link between the solar and the atmospheric neutrino oscillations: both solar and atmospheric neutrino data are compatible with $\theta_{13} = 0$ within the experimental sensitivity. The best experimental constraint to $\theta_{13}$ comes from the reactor experiment Chooz[24]: $\sin^2 2\theta_{13} \leq 0.14$ at 90% C.L. for $\Delta m_{23}^2 = 2.5 \cdot 10^{-3}$ eV$^2$.

The measurement of the mixing angle parameters can be performed in long-baseline oscillation experiments with suitable neutrino beams produced at accelerators, since this technique offers a better control over the neutrino flux. In particular three parameters, which are still to be measured, the mixing angle $\theta_{13}$, the CP phase $\delta_{CP}$ and sign($\Delta m_{23}^2$) can be determined by detecting subleading $\nu_\mu \rightarrow \nu_e$ oscillations, as discussed in Section[3].
2 Present generation of long-baseline experiments

Over the next five years the present generation of oscillation experiments at accelerators with long-baseline $\nu_\mu$ beams (Table 1), K2K at KEK [11], MINOS [25] at the NUMI beam from FNAL [26] and ICARUS [27] and OPERA [28] at the CNGS beam from CERN [29] are expected to confirm the atmospheric evidence of oscillations and measure $\sin^2 2\theta_{23}$ and $|\Delta m_{23}^2|$ within 10 ± 15 % of accuracy if $|\Delta m_{23}^2| > 10^{-3}$ eV$^2$. K2K and MINOS are looking for neutrino disappearance, by measuring the $\nu_\mu$ survival probability as a function of neutrino energy while ICARUS and OPERA will search for evidence of $\nu_\tau$ interactions in a $\nu_\mu$ beam, the final proof of $\nu_\mu \rightarrow \nu_\tau$ oscillations. K2K has already completed its data taking at the end of 2004, while MINOS has started data taking beginning 2005. CNGS is expected to start operations in the second half of 2006.

Table 1: Main parameters for present long-baseline neutrino beams

| Neutrino facility | Proton momentum (GeV/c) | L (km) | $E_\nu$ (GeV) | pot/yr ($10^{19}$) |
|-------------------|-------------------------|--------|---------------|-------------------|
| KEK PS            | 12                      | 250    | 1.5           | 2                 |
| FNAL NUMI         | 120                     | 735    | 3             | 20÷34             |
| CERN CNGS         | 400                     | 732    | 17.4          | 4.5÷7.6           |

In all these facilities conventional muon neutrino beams are produced through the decay of $\pi$ and K mesons generated by a high energy proton beam hitting needle-shaped light targets. Positive (negative) mesons are sign-selected and focused (defocused) by large acceptance magnetic lenses into a long evacuated decay tunnel where $\nu_\mu$'s ($\bar{\nu}_\mu$'s) are generated. In case of positive charge selection, the $\nu_\mu$ beam has typically a contamination of $\nu_\mu$ at few percent level (from the decay of the residual $\pi^-$, $K^-$ and $K^0$) and $\sim 1\%$ of $\nu_e$ and $\bar{\nu}_e$ coming from three-body $K^\pm$, $K_0$ decays and $\mu$ decays. The precision on the evaluation of the intrinsic $\nu_e$ to $\nu_\mu$ contamination is limited by the knowledge of the $\pi$ and $K$ production in the primary proton beam target. Hadroproduction measurements at 400 and 450 GeV/c performed with the NA20 [30] and SPY [31] experiments at the CERN SPS provided results with 5÷7% intrinsic systematic uncertainties.

Figure 1: Muon and electron neutrino flux spectra of the CNGS beam at the Gran Sasso Laboratories.

The CNGS $\nu_\mu$ beam has been optimized for the $\nu_\mu \rightarrow \nu_\tau$ appearance search. The beam-line design was accomplished on the basis of the previous experience with the WANF beam at CERN SPS [32]. The expected muon neutrino flux at the Gran Sasso site will have an average energy of 17.4 eV.
GeV and \( \sim 0.6\% \) \( \nu_e \) contamination for \( E_\nu < 40 \text{ GeV} \) (Fig. 1). Due to the long-baseline (L=732 Km) the contribution to neutrino beam from the \( K^0 \) and mesons produced in the reinteraction processes will be strongly reduced with respect to the WANF [33]: the \( \nu_e/\nu_\mu \) ratio is expected to be known within \( \sim 3\% \) systematic uncertainty [34].

Current long-baseline experiments with conventional neutrino beams can look for \( \nu_\mu \rightarrow \nu_e \) even if they are not optimized for \( \theta_{13} \) studies. MINOS at NuMI is expected to reach a sensitivity \( \sin^2 2\theta_{13} = 0.08 \) [25] integrating 14·10^{20} protons on target (pot) in 5 years according to the FNAL proton plan evolution [35]. MINOS main limitation is the poor electron identification efficiency of the detector. ICARUS [27] and OPERA [28] can reach a 90\% C.L. combined sensitivity \( \sin^2 2\theta_{13} = 0.030 \) (\( \Delta m^2_{23} = 2.5 \cdot 10^{-3} \text{ eV}^2 \), convoluted to CP and matter effects), a factor \( \sim 5 \) better than Chooz for five years exposure to the CNGS beam at nominal intensity for shared operation 4.5·10^{19} \text{ pot/yr} [36]. According to the CERN PS and SPS upgrade studies [38] the CNGS beam intensity could be improved by a factor 1.5, allowing for more sensitive neutrino oscillation searches for ICARUS and OPERA experiments.

It is worth mentioning that the sensitivity on \( \theta_{13} \) measurement of the current long-baseline experiments with conventional neutrino beams, like NUMI and CNGS, will be limited by the power of the proton source which determines the neutrino flux and the event statistics, by the not optimized \( L/E_\nu \) and by the presence of the \( \nu_e \) intrinsic beam contamination and its related systematics. This is particular true for CNGS where the neutrino energy, optimized to overcome the kinematic threshold for \( \tau \) production and to detect the \( \tau \) decay products, is about ten times higher the optimal value for \( \theta_{13} \) searches.

Another approach to search for non vanishing \( \theta_{13} \) is to look at \( \tau_e \) disappearance using nuclear reactors as neutrino source. A follow-up of Chooz, Double Chooz [39], has been proposed to start in 2008 with a two detectors setup, capable to push systematic errors down to 0.6 \% and to reach a sensitivity on \( \sin^2 2\theta_{13} \sim 0.024 \) (90\% C.L., \( \Delta m^2_{23} = 2.5 \cdot 10^{-3} \)) in a 3 years run.

A summary of \( \theta_{13} \) sensitivities for the present generation of experiments is reported Tab. 2 and in Fig. 2. The same data are reported in Fig. 4 as a function of the time, following the schedule reported in the experimental proposals.

### Table 2: The expected 90\% C.L. sensitivity on \( \theta_{13} \) measurements for the present and next generation long-baseline experiments with conventional \( \nu_\mu \) beams for \( \Delta m^2_{23} \sim 2.5 \cdot 10^{-3} \text{ eV}^2 \) (\( \delta_{\text{CP}} = 0 \)). The result of the reactor experiment Chooz is also shown as comparison.

| Experiment | fid. mass (Kt) | \( \sin^2 2\theta_{13} \) | \( \theta_{13} \) |
|------------|----------------|-----------------|---------------|
| MINOS      | 5.0            | 0.08            | 8.1°          |
| ICARUS     | 2.4            | 0.04            | 5.8°          |
| OPERA      | 1.8            | 0.06            | 7.8°          |
| Chooz      | 0.012          | 0.14            | 11°           |

## 3 The future experimental challenge: the sub-leading \( \nu_\mu \rightarrow \nu_e \) oscillations

The parameters \( \theta_{13}, \delta_{\text{CP}} \) and \( \text{sign}(\Delta m^2_{23}) \) can be extracted by measuring sub-leading \( \nu_\mu \rightarrow \nu_e \) oscillations. The \( \nu_e \) disappearance experiments, like reactor experiments, can address \( \theta_{13} \) searches but are not sensitive to \( \delta_{\text{CP}} \) and \( \text{sign}(\Delta m^2_{23}) \), while \( \nu_\mu \rightarrow \nu_e \) transitions could provide similar information of \( \nu_\mu \rightarrow \nu_e \) transitions but they are experimentally very challenging.
Figure 2: Expected sensitivity on $\theta_{13}$ mixing angle (matter effects and CP violation effects not included) for MINOS, ICARUS and OPERA combined at nominal CNGS and for the next T2K experiment, compared to the Chooz exclusion plot.

The $\nu_\mu \to \nu_e$ transition probability can be parameterized as [40]:

$P(\nu_\mu \to \nu_e) = 4c^2_{13}s^2_{13}s^2_{23}\sin^2\Delta m^2_{23}L \over 4E_\nu$

$+ 8c^2_{13}s_1s_2s_3(c_{12}c_{23}\cos\delta_{\text{CP}} - s_{12}s_{13}s_{23}) \cos \Delta m^2_{23}L \over 4E_\nu \sin \Delta m^2_{13}L \over 4E_\nu \sin \Delta m^2_{32}L \over 4E_\nu$

$- 8c^2_{13}c_{12}c_{23}s_1s_2s_3 \sin \delta_{\text{CP}} \sin \Delta m^2_{23}L \over 4E_\nu \sin \Delta m^2_{13}L \over 4E_\nu \sin \Delta m^2_{32}L \over 4E_\nu$

$+ 4s^2_{13}c^2_{13}\{c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_2s_{13}s_{13}s_{23}\cos\delta_{\text{CP}} \} \sin \Delta m^2_{32}L \over 4E_\nu$

$- 8c^2_{12}s^2_{13}s^2_{23} \cos \Delta m^2_{23}L \over 4E_\nu \sin \Delta m^2_{13}L \over 4E_\nu aL \over 4E_\nu (1 - 2s^2_{13}).$ (4)

The first line of this parameterization contains the term driven by $\theta_{13}$, the second and third contain CP even and odd terms respectively, and the forth is driven by the solar parameters. The last line parameterizes matter effects developed at the first order where $a [\text{eV}^2] = \pm 2\sqrt{2}\text{G}_F n_e E_\nu = 7.6 \cdot 10^{-5} \rho [\text{g/cm}^3] E_\nu [\text{GeV}]$. The CP odd term and matter effects change sign by changing neutrinos with antineutrinos.

The $\nu_\mu \to \nu_e$ transitions are dominated by the solar term, anyway, at the distance defined by the $\Delta m^2_{23}$ parameter, they are driven by the $\theta_{13}$ term which is proportional to $\sin^2 2\theta_{13}$. Below $\sin^2 2\theta_{13} \simeq 10^{-3}$ the "solar neutrino oscillation regime" will be again the dominant transition mechanism, limiting further improvements of the experimental sensitivity to $\theta_{13}$. Moreover, $P(\nu_\mu \to \nu_e)$ could be strongly influenced by the unknown value of $\delta_{\text{CP}}$ and $\text{sign}(\Delta m^2_{32})$. The contribution of the different terms of eq. (4) is shown in Fig. 3 as a function of the baseline for 1 GeV neutrinos in the solar oscillation region (left) and in the atmospheric oscillation region (right).

The measurement of $\theta_{13}$ represents the first mandatory ingredient for the investigation of the CP leptonic violation in the $\nu_\mu \to \nu_e$ transitions and for the mass hierarchy determination. The detection of the $\delta_{\text{CP}}$ phase will require a major experimental effort because of its intrinsic difficulty, relying on the need of disentangling several contributions to $\nu_\mu \to \nu_e$ oscillation probability.
Leptonic CP violation searches look for different behavior of neutrino and antineutrino appearance probabilities through the asymmetry

\[ A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{4E_\nu} \sin 2\theta_{12} \sin \theta_{13} \delta_{CP}. \]  

The effect of the CP violation will be proportional to \(1/\sin \theta_{13}\) while \(P(\nu_\mu \to \nu_e)\) is proportional to \(\sin^2 2\theta_{13}\). For large values of \(\theta_{13}\), \(A_{CP}\) will be small even if characterized by large number of oscillated events: systematic errors would be the main limiting experimental effect. For small values of \(\theta_{13}\), event statistics and background rates would be the ultimate limitation to the search. Matter effects also produce differences between \(P(\nu_\mu \to \nu_e)\) and \(P(\overline{\nu}_\mu \to \overline{\nu}_e)\): they depend from the baseline and to the neutrino energy and could increase or decrease the overall probabilities depending on \(\text{sign}(\Delta m_{23}^2)\). At baselines of \(\sim 100\) km these effects are negligible while at \(\sim 700\) km they can be up to \(\sim 30\%\) of the probabilities in vacuum.

The richness of the \(\nu_\mu \to \nu_e\) transition is also its weakness: it will be very difficult for pioneering experiments to extract all the genuine parameters unambiguously. Correlations are present between \(\theta_{13}\) and \(\delta_{CP}\) \[41\]. Moreover, in absence of information about the sign of \(\Delta m_{23}^2\) \[42, 43\] and the approximate \([\theta_{23}, \pi/2 - \theta_{23}]\) symmetry for the atmospheric angle \[44\], additional clone solutions rise up. In general, the measurement of \(P(\nu_\mu \to \nu_e)\) and \(P(\nu_\tau \to \nu_\tau)\) will result in eight allowed regions of the parameter space, the so-called eightfold-degeneracy \[43\].

\(\theta_{13}\) searches look for experimental evidence of \(\nu_e\) appearance in excess to what expected from the solar terms. These measurements will be experimentally hard because the Chooz limit on the \(\overline{\nu}_e\) disappearance, \(\theta_{13} < 11^\circ\) for \(\Delta m_{23}^2 \approx 2.5 \times 10^{-3} \text{ eV}^2\), translates into a \(\nu_\mu \to \nu_e\) appearance probability less than 10% at the appearance maximum in a high energy muon neutrino beam. Furthermore, as already pointed out, the \(\nu_\mu \to \nu_e\) experimental sensitivity with conventional \(\nu_\mu\) beams is limited by an unavoidable \(\nu_e\) beam contamination of about 1%. The \(\nu_\mu\) to \(\nu_\tau\) oscillations,
with \( E_p \) above the \( \tau \) mass production threshold, generate background due to a significant number of \( \nu_\tau \) charged current interactions where a large fraction of \( \tau \)'s decay into electrons. Finally, neutral pions in both neutral current or charged current interactions can fake an electron providing also a possible background for the \( \nu_e \)’s.

Therefore the measurement of \( \theta_{13} \) mixing angle and the investigation of the leptonic CP violation will require:

- neutrino beams with high performance in terms of intensity, purity and low associated systematics. Event statistics, background rates and systematic errors will play a decisive role in detecting \( \nu_e \) appearance;

- the use of detectors of unprecedented mass, granularity and resolution. Again event statistics is the main concern, while high detector performances are necessary to keep the event backgrounds (as \( \pi^0 \) from \( \nu_\mu \) neutral current interactions, mis-identified as \( \nu_e \) events) at low as possible rate;

- ancillary experiments to measure the meson production (for the neutrino beam knowledge), the neutrino cross-sections, the particle identification capability. The optimization of proton driver characteristics and the best possible estimation of the systematic errors will require this kind of dedicated experiments. The Harp hadroproduction experiment at CERN PS \[45\] took data for primary protons between 3 and 14.5 GeV in 2001 and 2002 with different target materials. These data are expected to contribute to the proton driver optimization, the determination of the K2K and MiniBooNE neutrino beam fluxes and to the study of atmospheric neutrino interaction rates.

The intrinsic limitations of conventional neutrino beams are overcome if the neutrino parents can be fully selected, collimated and accelerated to a given energy. This can be attempted within the muon or a beta decaying ion lifetimes. The neutrino beams from their decays would then be pure and perfectly predictable. The first approach brings to the Neutrino Factories \[46\], the second to the BetaBeams \[48\]. However, the technical difficulties associated with developing and building these novel conception neutrino beams suggest for the middle term option to improve the conventional beams by new high intensity proton machines, optimizing the beams for the \( \nu_\mu \to \nu_e \) oscillation searches. They are called SuperBeams \[40\].

Different detection techniques of neutrino interactions based on water Cerenkov (WC), liquid Argon (LAr), nuclear emulsions and calorimetry are available to build very massive detectors according to the intrinsic neutrino beam characteristics, energy and composition as discussed in the following section.

### 4 Massive neutrino detectors

Several experimental techniques have been recently exploited for high energy neutrino detection and new set-up are under consideration to cope with the challenges of precision neutrino physics at accelerators. Compared with other high energy detectors, they must offer unprecedented fiducial masses, instrumented with cheap and reliable active detector technologies guarantying high granularity, good energy resolution and excellent particle identification capability. The most relevant technologies developed so far are discussed in the following and summarized in Tab. \[4\].

#### 4.1 Water Cerenkov Detector

Besides the observation of solar and supernovae neutrinos, the discovery of neutrino oscillations in the atmospheric sector represents another great success of the Cerenkov technique. The target material and the possibility to instrument only the vessel surface make these detectors relatively cheap, so that huge fiducial masses are conceivable.

Charged tracks above the Cerenkov threshold emit about 390 photons/cm with a wavelength between 300 and 700 nm. Light attenuation in water, as measured in Super-Kamiokande, is 98
Charged leptons are identified through the detection of Cerenkov light, exploiting the features of the rings for particle identification. A muon scatters very little crossing the detector. Therefore, the associated ring has very sharp edges. Conversely, an electron scatters (showers) much more, producing rings with “fuzzy” edges. The total measured light gives an estimate of the lepton energy, while the time measurement provided by each photomultiplier determines the outgoing lepton direction and the position of the neutrino interaction vertex. By combining all this information it is possible to fully reconstruct the energy, the direction and the flavor of the incoming neutrino. It is worth noting that the procedure discussed above is suitable only for quasi-elastic events ($\nu_l n \rightarrow l^- p$). Indeed, for non quasi-elastic events there are other particles in the final state, carrying a large energy fraction, that are either below the Cerenkov threshold or neutrals, resulting in a poor measurement of the total event energy. Furthermore, the presence of more than one particle above threshold produces more than one ring, spoiling the particle identification capability of the detector.

In the SNO experiment a Cerenkov detector using heavy water as target is employed for the detection or solar neutrinos. Besides the features discussed above, the SNO detector is also able to identify neutral current neutrino interactions through the detection of the neutron produced in the reaction $\nu_l d \rightarrow \nu_l pn$.

Water Cerenkov is a mature technology that demonstrated a valuable cost effectiveness and excellent performances at low neutrino energies. A detector with a fiducial mass as large as 20 times Super-Kamiokande could be built and would be an optimal detector for neutrino beams with energies around or below 1 GeV. Furthermore, such a device could represent the ultimate tool for proton decay searches, and for atmospheric neutrinos and supernovae neutrinos detection.

### 4.2 Magnetized Iron Calorimeter

Magnetized iron calorimeters are used since the seventies when the HPWF experiment discovered neutrino induced charm-production. Calorimeters consist of magnetized iron slabs and tracking detectors that act both as target and muon spectrometer. The main feature of these detectors is their excellent muon reconstruction (charge and momentum) and their high density (short interaction length) that minimizes the background due to pion and kaon decays, and to punch-through hadrons.

The MINOS Collaboration has built a magnetized iron calorimeter to study neutrino oscillations at the atmospheric scale by using the NuMI long-baseline beam. The detector is composed of 2.54 cm-thick steel planes interleaved with planes of 1 cm-thick and 4.1 cm-wide scintillator strips. The iron is magnetized to an average field of about 1.5 T. Simulations, as well as test beam results, show that the energy resolution $\Delta E/E$ of this tracking calorimeter is $55\%/\sqrt{E(\text{GeV})}$ and $23\%/\sqrt{E(\text{GeV})}$ for hadronic and electromagnetic showers, respectively. This technology is particularly suited for the measurement of $\nu_\mu CC$ events, while the electron identification is rather poor. Therefore, magnetized iron calorimeters are planned to be used to study either $\nu_\mu$ appearance in a pure $\nu_e$ beam or $\nu_\mu$ disappearance in a well known $\nu_\mu$ beam. It is worth noting that the presence of the magnetic field is essential in order to tag the (anti-)neutrino in the final state when such a detector is exploited in a non-pure beam, i.e. conventional neutrino beams and Neutrino Factories (see Section 5.3). This technology has been proposed as a detector for atmospheric neutrinos, Monolith, and to study the so-called “golden channels” $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ at a Neutrino Factory.

### 4.3 Low Z Calorimeter

Unlike the iron calorimeters discussed in Section, low Z calorimeters allow a good identification and energy measurement of electrons produced in $\nu_e$ charged current interactions. In fact, for this purpose one must sample showers more frequently than 1. $X_0$ and a magnetic field is not necessary. Another advantage of a low Z calorimeter is that, for a given sampling in units of radiation length, one can have up to a factor 3 more mass per readout plane with respect to iron calorimeters. This
| Detector Technology          | Mass (kton) | Event by event id | Magnetic Field | $\nu$ energy (GeV) |
|-----------------------------|-------------|-------------------|----------------|-------------------|
| Water Cerenkov              | 50          | OK                 | OK             | 0.005 - 10        |
| Magnetic iron calorimeter   | 5.4         | OK                 | OK             | > 0.5             |
| Low Z calorimeter           | 30 (project)| OK                 | OK             | 0.1-10            |
| Nuclear Emulsions (ECC)     | 1.8         | OK                 | OK             | 1-100             |
| Liquid Argon TPC            | 0.6 → 3.0   | OK                 | External       | 0.001-100         |

Table 3: Comparison of the main features of the experimental techniques discussed in the previous sections.

A detector can discriminate between NC and $\nu_e$ induced charged current events by looking at the longitudinal profile of the neutrino interaction, as neutral current events are likely to be much more spread out in the detector than $\nu_e$CC. Several active detectors (Resistive Plate Chambers, streamer tubes, plastic and liquid scintillators) have been considered and are currently under investigation. The liquid scintillator technique has been proposed by the NO$\nu$A experiment to search for $\nu_\mu \rightarrow \nu_e$ oscillations in the NUMI Off-Axis beam-line [57]. The far detector will be composed solely of liquid scintillator encased in a 15.7 m long cell titanium dioxide-loaded PVC extrusions where each cell is 3.9 cm wide and 6 cm deep.

4.4 Hybrid Emulsion Detector

The Emulsion Cloud Chamber (ECC) concept (see references quoted in [28]), a modular structure made of a sandwich of passive material plates interspersed with emulsion layers, combines the high-precision tracking capabilities of nuclear emulsions and the large mass achievable by employing metal plates as a target. By assembling a large quantity of such modules, it is possible to conceive and realize $\mathcal{O}(Kton)$ fine-grained vertex detector optimized for the study of $\nu_\tau$ appearance. It has been adopted by the OPERA Collaboration for a long-baseline search of $\nu_\mu \rightarrow \nu_\tau$ oscillations at the CNGS beam through the direct detection of the $\tau$’s produced in $\nu_\tau$ charged current interactions. As an example of $\tau$ detection with ECC, we show in Fig. 4 the $\nu_\tau$ events observed in the DONUT experiment [58].

The basic element of the OPERA ECC is a “cell” made of a 1 mm thick lead plate followed by a thin emulsion film which consists of 44 $\mu$m-thick emulsion layers on either side of a 200 $\mu$m plastic base. The number of grains hits in each emulsion layer (15-20) ensures redundancy in the measurement of particle trajectories and allows the measurement of their energy loss that, in the non-relativistic regime, can help to distinguish between different mass hypotheses.

Thanks to the dense ECC structure and to the high granularity provided by the nuclear emulsions, the detector is also suited for electron and $\gamma$ detection. The energy resolution for an electromagnetic shower is about 20%. Nuclear emulsions are able to measure the number of grains associated to each track. This allows a two-track separation at $\sim 1 \mu$m or even better. Therefore, it is possible to disentangle single-electron tracks from electron pairs coming from $\gamma$ conversion in lead. This outstanding position resolution can also be used to measure the angle between different track segments with an accuracy of about 1 mrad: this allows the use of Coulomb scattering to evaluate the particle momentum with a resolution of about 20%, and to reconstruct the kinematical event variables.

A lead-emulsion detector has been also proposed to operate at a Neutrino Factory to study the “silver channel” $\nu_e \rightarrow \nu_\tau$ [59, 60] (see Section 5.3).
4.5 Liquid Argon Time Projection Chamber

The technology of the Liquid Argon Time Projection Chamber (LAr TPC), first proposed by C. Rubbia on 1977 [61], was conceived as a new tool for a completely uniform imaging with high accuracy of very massive volumes, continuously sensitive and self-triggering.

The operating principle of this kind of detector is rather simple: any ionizing event (from a particle decay or interaction) taking place in the active LAr volume, which is maintained at a temperature $T \sim 89$ K, produces ion-electron pairs. In the presence of a strong electric field ($\sim 0.5$ KV/cm), the ions and electrons drift. The faster electrons are collected by anode wire planes with different orientations located near the end of the sensitive volume. The knowledge of the wire positions and the drift time provides the three-dimensional image of the track, while the charge collected on the wires provides precise information on the deposited energy.

The detector developed by the ICARUS Collaboration [27], consists of a large vessel of liquid Argon filled with three planes of wires strung on the different orientations. The device allows tracking, $dE/dx$ measurements and a full-sampling electromagnetic and hadronic calorimetry. Furthermore, the imaging provides excellent electron and photon identification and electron/hadron separation. The energy resolution $\Delta E/E$ is excellent for electromagnetic showers ($\sim 11%/\sqrt{E$(MeV)}$), $E < 50$ MeV [62], $3%/\sqrt{E$(GeV)} $1% [27]) and also very good for contained hadronic showers ($30%/\sqrt{E$(GeV)}$). Furthermore, it is possible to measure the momentum of muons with a resolution better than 20% by using multiple Coulomb scattering (3% for stopping muons where momentum is measured from range).

The most important milestone of this technique has been the successful operation of the ICARUS 600 tons prototype [63], which has operated during the summer of 2001 and it is now installed in the Gran Sasso laboratories. An event recorded with the 600 tons detector is shown in Fig. 5. A 3 kton detector is designed to operate with the CNGS neutrino beam to search for $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations. Given its excellent electron identification capabilities, it has been also...
proposed to operate on new other neutrino beams to search for $\nu_\mu \rightarrow \nu_e$ appearance.

A 100 kton LAr detector has been proposed [64] for a next future generation experiment which would deliver excellent physics output in rare event search and neutrino physics. However, new concepts and R&D studies are required to extrapolate this technology further. The proposed detector would be composed by a single “boiling” cryogenic tanker, with external dimensions of 40 m in height and 70 m in diameter. The charge imaging, scintillation and Cerenkov light readout allow a complete and redundant event reconstruction. The detector will be running in bi-phase mode, liquid plus gas, in order to allow for drift lengths as long as $\sim 20$ m along a drift electric field of $\sim 1$ KV/cm. The drift electrons produced in the liquid phase are extracted from the liquid into the gas by a suitable electric field and then amplified near the anodes.

5 New facilities for next generation of neutrino oscillation experiments

As pointed out above, different options for neutrino beams of novel conception are presently under study for the next generation of the long-baseline neutrino oscillation experiments. Different time scales can be envisaged according to the technical difficulties associated with the developing and the building these facilities.

The first facility will probably be neutrino SuperBeams: conventional neutrino beams characterized by megawatt power proton drivers (Section 5.1). Neutrino SuperBeams will require the development of high power proton Linacs or Rapid Cycling Synchrotrons, expected to happen in...
the next decade, and the development of proton targets able to survive to megawatt power proton beams, whose R&D studies have already started [65].

Neutrino SuperBeams can be seen as the injector stage of Neutrino Factories (Section 5.3), where the other daughters of pion decays, the muons, are collected, cooled down, accelerated and stored in a decay ring where neutrinos are produced. The muon manipulation, acceleration and storage will require the development of novel machines in high energy physics accelerators with a consequent timescale of the order of about 20 years [66].

In BetaBeams (Section 5.2) neutrinos are produced by the decay of radioactive heavy ions after proper acceleration. In principle all the machinery for ion production and acceleration has been already developed at CERN for the heavy ion physics program at Isolde and SPS. The required improvement by about 3 orders of magnitude of the presently available ion fluxes will require sub-megawatt, 1-2 GeV Linacs, new target developments for heavy ion production, ion collection and acceleration system including the CERN PS and SPS and a novel decay ring. Accounting for the technical challenges involved in the above facilities, the expected timescale of BetaBeams could be intermediate between SuperBeams and Neutrino Factories. A design study of BetaBeam is just started within the European project Eurisol [67] aimed at a very intense source of heavy ions.

5.1 Near-term long-baseline experiments with SuperBeams

According to the present experimental situation, conventional neutrino beams can be improved and optimized for the $\nu_\mu \rightarrow \nu_e$ searches. The design of a such new SuperBeam facility for a very high intensity and low energy $\nu_\mu$ flux will demand:

- a new higher power proton driver, exceeding the megawatt, to deliver more intense proton beams on target;
- a tunable $L/E_\nu$ in order to explore the $\Delta m^2_{23}$ parameter region as indicated by the previous experiments with neutrino beams and atmospheric neutrinos;
- narrow band beams with $E_\nu \sim 1 \div 2$ GeV;
- a lower intrinsic $\nu_e$ beam contamination which can be obtained suppressing the $K^+$ and $K^0$ production by the primary proton beam in the target.

An interesting option for the SuperBeams is the possibility to tilt the beam axis a few degrees with respect to the position of the far detector (Off-Axis beams) [52, 68]. According to the two body $\pi$-decay kinematics, all the pions above a given momentum produce neutrinos of similar energy at a given angle $\theta \neq 0$ with respect to the direction of parent pion (contrary to the $\theta = 0$ case where the neutrino energy is proportional to the pion momentum). These neutrino beams have several advantages with respect to the corresponding on-axis ones: they are narrower, lower energy and with a smaller $\nu_e$ contamination (since $\nu_e$ mainly come from three body decays) although the neutrino flux can be significantly smaller.

In the JHF project Phase I (T2K experiment [52]) a 50 GeV/c proton beam of 0.75 MW from a PS will produce a very intense $\pi$ and $K$ beam tilted by $\theta = 2^\circ$ with respect to the position of Super-Kamiokande detector at 295 Km of distance. The experiment is approved: data taking is scheduled to start in 2009 (10 % of the project’s pot intensity is expected the first year of run). The resulting 700 MeV $\nu_\mu$ beam (Fig. 6) with 0.4% $\nu_e$ contamination will allow to reach a 90 % C.L. sensitivity $\sin^2 2\theta_{13} \sim 0.006$ in five years, assuming $\delta_{CP} = 0$, a factor 20 better than the current limit set by Chooz, see Fig. 5. T2K will also measure $\Delta m^2_{23}$ and $\sin^2 2\theta_{23}$ with $\sim 2\%$ precision detecting $\nu_\mu$ disappearance and will perform a sensitive search for sterile neutrinos through the detection of neutral current event disappearance.

The T2K sensitivity compared to the ones of the present generation experiments, is reported in Fig. 7 as a function of the time.

The foreseen machine upgrade to 4 MW (JHF-II), in conjunction with the construction of a very large (0.54 Mton fiducial volume) water Čerenkov detector (Hyper-Kamiokande) will allow to
investigate the CP violation phase (J-Parc II). In a 5 years run with the $\nu_\mu$ beam, the experiment could reach a 90% C.L. $\theta_{13}$ sensitivity $\sin^2 2\theta_{13} > 6 \times 10^{-4}$, while with 2 years of $\nu_\mu$ and 6 years of $\bar{\nu}_\mu$ operations, it will discover a non vanishing $\delta_{CP}$ at a 3$\sigma$ level or better if $\sin |\delta_{CP}| > 20^\circ$ and $\sin^2 2\theta_{13} \sim 0.01$ [69] (see also Fig.12).

![Figure 6: T2K neutrino beam energy spectrum for different off-axis angle $\theta$.](image)

The NO$\nu$A experiment with an upgraded NuMI Off-Axis neutrino beam [57] ($E_\nu \sim 2$ GeV and a $\nu_e$ contamination less than 0.5%) and with a baseline of 810 Km (12 km Off-Axis), was recently proposed at FNAL with the aim to explore the $\nu_\mu \rightarrow \nu_e$ oscillations with a sensitivity 10 times better than MINOS. If approved in 2006 the experiment could start data taking in 2011. The NuMI target will receive a 120 GeV/c proton flux with an expected intensity of $6.5 \times 10^{20}$ pot/year (2 $\times$ $10^7$ s/year are considered available to NuMI operations while the other beams are normalized to $10^7$ s/year). The experiment will use a near and a far detector, both using liquid scintillator. In 5 years of data taking, with 30 Kt active mass far detector a sensitivity on $\sin^2 2\theta_{13}$ slightly better than T2K, as well as a precise measurement of $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$, can be achieved. NO$\nu$A can also allow to solve the mass hierarchy problem for a limited range of the $\delta_{CP}$ and $\text{sign}(\Delta m^2_{23})$ parameters [57].

As a second phase, the new proton driver of 8 GeV/c and 2 MW, could increase the NuMI beam intensity to $17.2 \pm 25.2 \times 10^{20}$ pot/year, allowing to improve the experimental sensitivity by a factor two and to initiate the experimental search for the CP violation.

A longer term experiment has been proposed at BNL for a different long-basedline neutrino beam [70]. In this proposal the AGS 28 GeV PS should be upgraded to 1 MW and a neutrino beam with $\langle E_\nu \rangle \simeq 1.5$ GeV should be fired into a megaton water Cerenkov detector at a baseline of 2540 km. The detector would be at the second oscillation maximum and the comparison of $\nu_\mu$ disappearance and $\nu_e$ appearance at the first and second oscillation maximum could allow a better control of degeneracies. However, it should be noted that background rates and signal efficiency of a water Cerenkov detector in this energy range are not optimal and not constant between the first and the second maximum. In 5 years run this experiment could reach a 90 % C.L. sensitivity $\sin^2 2\theta_{13} \simeq 0.003$ ($\delta_{CP} = 0$).

The performances of future neutrino oscillation experiments are summarized in Tab. 4 (see also Refs. [71]).

5.1.1 European Superbeam projects

Many ideas and approaches have been developed for neutrino long-basedline experiments in Europe after the CNGS $\nu_\tau$ appearance phase. These projects are aiming to improve and develop existing
Figure 7: Evolution of sensitivities on $\sin^2 2\theta_{13}$ as function of time. For each experiment are displayed the sensitivity as function of time (solid line) and the world sensitivity computed without the experiment (dashed line). The comparison of the two curves shows the discovery potential of the experiment along its data taking. The world overall sensitivity along the time is also displayed. The comparison of the overall world sensitivity with the world sensitivity computed without a single experiment shows the impact of the results of the single experiment. Experiments are assumed to provide results after the first year of data taking.

infrastructures and detectors or considering new neutrino beams and detectors.

The possibility to improve the CERN to Gran Sasso neutrino beam performances for $\theta_{13}$ searches even with the present proton beam, $E_p = 400$ GeV and $4.5 \cdot 10^{19}$ pot/year was investigated (CNGS-L.E.) [72]. The low energy neutrino flux can be increased by a factor 5 with respect to the current CNGS beam by an appropriate optimization of the target (a compact 1 m carbon rod) and of the focusing system. The decay tunnel will be reduced to 350 m allowing for a near detector useful for determining beam composition. This intense low energy neutrino flux, $E_{\nu_e} \simeq 1.8$ GeV, will produce $4.5 \nu_{\mu}$-CC/10$^{19}$ pot/Kt event rate with 0.9% $\nu_{e}/\nu_{\mu}$-CC event contamination. With this low energy CNGS-L.E. neutrino beam, the sensitivity to $\sin^2 2\theta_{13}$ can be increased by a factor 7 with respect to Chooz, $\sin^2 2\theta_{13} < 0.02$ (not accounting for CP violation and matter effects) in 5 years with a 2.4 Kt fiducial mass liquid Argon detector by assuming $\Delta m_{23}^2 = 2.5 \cdot 10^{-3}$ eV$^2$, Fig. 8. However, the preparation of a such low energy neutrino facility wouldn’t be compatible with the CNGS beam for $\nu_\tau$ programme and will require a suitable interval of time after the CNGS $\tau$-phase running for the "radioactive cooling" of the target and of decay tunnel in order to change the target geometry, shorten and enlarge the decay tunnel, in a safe environment. Alternatively a new beam line should be build.

A second study considered again a low energy neutrino beam (1.5 GeV mean energy) fired into a detector made of 44,000 phototubes deployed in the Golfo di Taranto at 1000 m depth, 1200 km from CERN (CNGT), $2^\circ$ degrees off-axis, equipping 2 Mton of water [73]. In this case the detector would be placed at the second oscillation maximum and if movable it could take data both at the
minimum and at the maximum of oscillation probability. Sensitivity would be marginally worse than T2K in a 5 years data taking \[73\].

A proton driver was also recently studied to optimize the search for the \(\nu_\mu \rightarrow \nu_e\) oscillations with a new generation of low energy and high intensity SuperBeam \[74\]. In term of proton economics, the optimum beam energy turns out to be around 20 GeV, well matched to a 732 Km of baseline (i.e. CERN - Gran Sasso: average neutrino energy \(E_\nu \sim 1.6\) GeV). Roughly a \(\sin^22\theta_{13} \simeq 0.005\) sensitivity for \(\Delta m_{23}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2\), assuming \(\delta_{\text{CP}} = 0\) and no matter effects, can be obtained for \(2 \times 10^{22}\) pot/year (about two orders of magnitude higher than the intensity deliverable by the current CERN-PS) and 5 years exposure of ICARUS. The performance of this facility, indicated as PS++, has been computed for a power source corresponding to 6.5 MW accounting for a useful beam time operation of \(10^7\) s per year and a 2.35 kton detector: anyway the same sensitivity can be reached with 4 MW power if a LNGS hall is fully occupied by ICARUS (about 4 kton).

Figure 8: Expected sensitivity on \(\theta_{13}\) mixing angle (CP violation and matter effects not included in the calculation) for a 20 GeV/c high intensity PS proton beam from CERN to Gran Sasso (PS++) and for the ICARUS 2.4 Kton at the CNGS-L.E. compared to T2K experiment.

In the CERN-SPL SuperBeam project \[75\] \[76\] \[77\] the planned 4MW SPL (Superconducting Proton Linac) would deliver a 2.2 GeV/c proton beam, on a Hg target to generate an intense \(\pi^+\) (\(\pi^-\)) beam focused by a suitable magnetic horn in a short decay tunnel. As a result an intense \(\nu_\mu\) beam, will be produced mainly via the \(\pi\)-decay, \(\pi^+ \rightarrow \nu_\mu\) \(\mu^+\) providing a flux \(\phi \sim 3.6 \times 10^{11} \nu_\mu/\text{year/m}^2\) at 130 Km of distance, and an average energy of 0.27 GeV (Fig. 9). The \(\nu_e\) contamination from \(K\) will be suppressed by threshold effects and the resulting \(\nu_e/\nu_\mu\) ratio (\(\sim 0.4\%\)) will be known within 2\% error. The use of a near and far detector (the latter at \(L = 130\) Km of distance in the Frejus area) will allow for both \(\nu_\mu\)-disappearance and \(\nu_\mu \rightarrow \nu_e\) appearance studies. The physics potential of the 2.2 GeV SPL SuperBeam (SPL-SB) with a water Cerenkov far detector fiducial mass of 440 Kt \[51\] has been extensively studied \[76\]. The experimental sensitivity is displayed, due to the strong \(\theta_{13} - \delta_{\text{CP}}\) correlation, in the \((\theta_{13} - \delta_{\text{CP}})\) plane having fixed \(\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2\) (Fig. 11). The 90 \% C.L. \(\theta_{13}\) sensitivity (\(\delta_{\text{CP}} = 0\)) is \(\sin^22\theta_{13} = \sin^2 \cdot 0.002\) (5 years \(\nu_\mu\) beam), see Tab. 4. The corresponding \(3 \sigma\) CP violation discovery potential (2 years with \(\nu_\mu\) beam and 8 years with the reversed polarity \(\overline{\nu}_\mu\) beam) is shown in Fig. 12.

New developments show that the potential of the SPL-SB potential could be improved by rising
the SPL energy to 3.5 GeV \[78\], to produce more copious secondary mesons and to focus them more efficiently. This seems feasible if status of the art RF cavities would be used in place of the old foreseen LEP cavities \[79\]. In this upgraded configuration neutrino flux could be increased by a factor 3 with with respect to the 2.2 GeV configuration, reaching a sensitivity to $\sin^2 2\theta_{13}$ 8 times better than T2K and allowing to discovery CP violation (at 3 $\sigma$ level) if $\delta_{CP} \geq 25^\circ$ and $\theta_{13} \geq 1.4^\circ$ \[80\]. The expected performances are shown in Fig. 11 and Fig. 12.

Figure 9: Left: neutrino flux of $\beta$-Beam ($\gamma_{6He} = 60$, $\gamma_{18Ne} = 100$, shared mode) and CERN-SPL SuperBeam, 2.2 GeV, at 130 Km of distance. Right: the same for $\gamma_{6He} = 100$, $\gamma_{18Ne} = 100$, (non shared mode, that is just one ion circulating in the decay ring) and a 3.5 GeV SPL SuperBeam.

### 5.2 BetaBeams

BetaBeams ($\beta$B) have been introduced by P. Zucchelli in 2001 \[48\]. The idea is to generate pure, well collimated and intense $\nu_e$ ($\overline{\nu}_e$) beams by producing, collecting, accelerating radioactive ions and storing them in a decay ring in 10 ns long bunches, to suppress the atmospheric neutrino backgrounds. The resulting $\beta$B would be virtually background free and fluxes could be easily computed by the properties of the beta decay of the parent ion and by its Lorentz boost factor $\gamma$.

The best ion candidates so far are $^{18}Ne$ and $^{6}He$ for $\nu_e$ and $\overline{\nu}_e$ respectively. Summarizing, the

Figure 10: A schematic layout of the BetaBeam complex. At left, the low energy part is largely similar to the EURISOL project \[67\]. The central part (PS and SPS) uses existing facilities. At right, the decay ring has to be built.
main features of a neutrino beam based on the BetaBeams concept are:

- the beam energy depends on the $\gamma$ factor. The ion accelerator can be tuned to optimize the sensitivity of the experiment;
- the neutrino beam contains a single flavor with an energy spectrum and intensity known a priori. Therefore, unlike conventional neutrino beams, close detectors are not necessary to normalize the fluxes;
- neutrino and anti-neutrino beams can be produced with a comparable flux;
- differently from SuperBeams, BetaBeams experiments search for $\nu_e \rightarrow \nu_\mu$ transitions, requiring a detector capable to identify muons from electrons. Moreover, since the beam does not contain $\nu_\mu$ or $\bar{\nu}_\mu$ in the initial state, magnetized detectors are not needed. This is in contrast with the neutrino factories (see below) where the determination of the muon sign is mandatory.

A baseline study for a Beta Beam complex (Fig. 10) has been carried out at CERN [81]. The SPS could accelerate $^{6}$He ions at a maximum $\gamma$ value of $\gamma_{^{6}\text{He}} = 150$ and $^{18}$Ne ions up to $\gamma_{^{18}\text{Ne}} = 250$. In this scenario the two ions circulate in the decay ring at the same time. This is a feasible option, provided that their $\gamma$ are in the ratio $\gamma_{^{6}\text{He}}/\gamma_{^{18}\text{Ne}} = 3/5$. The reference $\beta B$ fluxes are $2.9 \times 10^{18}$ $^{6}$He useful decays/year and $1.1 \times 10^{18}$ $^{18}$Ne decays/year if the two ions are run at the same time in the complex. The resulting neutrino fluxes are displayed in Fig. 9. The water Čerenkov could be a suitable technology for a large detector. The physics potential has been computed in [82] for $\gamma_{^{6}\text{He}} = 60$, $\gamma_{^{18}\text{Ne}} = 100$ and with a 440 kton detector at 130 km, they are displayed in Fig. 11 and Fig. 12 Sensitivities taking into account all the parameter degeneracies and ambiguities scenario have been computed in [83].

![Figure 11: $\theta_{13}$ 90% C.L. sensitivity as function of $\delta_{CP}$ for $\Delta m_{23}^2 = 2.5 \times 10^{-3} eV^2$, \text{sign}(\Delta m_{23}^2) = 1, 2\% systematic errors. CNGS and T2K curves are taken from [37], BNL from [70], Double Chooz from [39], SPL-SB sensitivities have been computed for a 5 years $\nu_\mu$ run, $\beta B$ and $\beta B_{100,100}$ for a 5 years $\nu_e + \bar{\nu}_e$ run.

Novel developments, suggesting the possibilities of running the two ions separately at their optimal $\gamma$ [84], have recently triggered a new optimal scheme for the BetaBeam. In this scheme
Figure 12: $\delta_{CP}$ discovery potential at 3σ (see text) computed for 10 years running time. The SPL-SB 2.2 and 3.5 GeV, BetaBeam with $\gamma = 60, 100$ and $\gamma = 100, 100$ J-Parc II [69] and SPL-SB combined with BetaBeam are shown. All the curves are computed with a 2% systematic error, 10 years of data taking.

both ions are accelerated at $\gamma = 100$. The expected performances are displayed ($\betaB_{100,100}$) in Figs. 11 and 12. A sensitivity to $\sin^2 2\theta_{13}$ 30 times better than T2K could be reached and lepton CP violation could be discovered at 3 $\sigma$ if $\delta_{CP} \geq 25^\circ$ and $\theta_{13} \geq 1.0^\circ$ [80, 85].

BetaBeams require a proton driver in the energy range of 1-2 GeV, 0.5 MWatt power. The SPL can be used as injector, at most 10% of its protons would be consumed. This allows a simultaneous $\betaB$ and SPL-SB run, the two neutrino beams having similar neutrino energies (see also Fig. 9). The same detector could then be exposed to $2 \times 2$ beams ($\nu_\mu$ and $\bar{\nu}_\mu \times \nu_e$ and $\bar{\nu}_e$) having access to CP, T and CPT violation searches in the same run. With this combination of neutrino beams a sensitivity to $\sin^2 2\theta_{13}$ 35 times better than T2K could be reached exploiting a CP violation discovery potential at 3 $\sigma$ if $\delta_{CP} \geq 18^\circ$ and $\theta_{13} \geq 0.55^\circ$ [86] (Figs. 11 and 12).

BetaBeam capabilities for ions accelerated at higher energies than those allowed by SPS have been computed in [85, 86, 87]. All these studies assume that the same ion fluxes of the baseline scenario can be maintained. However, this is not the case if the number of stored bunches is kept constant in the storage ring. On the other hand, by increasing $\gamma$ (i.e. the neutrino energy) the atmospheric neutrinos background constraint on the total bunch length [48] tends to vanish. Studies are in progress at CERN in order to define realistic neutrino fluxes as a function of $\gamma$ [84]. It is worth noting that if a high intensity Beta Beam with $\gamma \sim 300 \div 500$ (requiring a higher energy accelerator than SPS, like the Super-SPS [88]) can be built, a 40 kton iron calorimeter located at the Gran Sasso Laboratory will have the possibility to discover a non vanishing $\delta_{CP}$ if $\delta_{CP} > 20^\circ$ for $\theta_{13} \geq 2^\circ$ (99% C.L.) and measure the sign of $\Delta m^2_{23}$ [80].

5.3 Neutrino Factories

The neutrino production by muon decay from a pure muon beam has been considered since 1998 [48]: this is indeed a perfectly well known weak process and the $\mu$ beam can be well measured in momentum and intensity.
Table 4: Summary table of different LBL options. J-Parc II \( \sin^2 2\theta_{13} \) sensitivity is extrapolated from T2K phase I. All the experiment are normalized to 5 years data taking considering a neutrino beam time operation of \( 10^7 \) s per year. Numbers quoted for \( \text{No} \nu A \) refer to the standard and the proton driver options (see text). SPL numbers are for the 2.2 GeV option (the 3.5 GeV performances are in parentheses). The \( \beta B \) columns is computed for the \( \gamma = 60, 100 \) option (the \( \gamma = 100, 100 \) performances are in parentheses), the \( \nu CC \) line indicates the sum of \( \nu_e^{CC} \) and \( \nu_{\mu}^{CC} \) rates. The \( \pi^0/\nu_e \) line indicates the fraction of the neutral current background normalized to intrinsic \( \nu_e \) background. Once fixed \( L/E_{\nu} \) to well match the \( \Delta m^2_{23} \) value, the figure of merit of the neutrino beam is determined by the \( \nu_{\mu}-CC/\text{Kt/year} \) event rate and also by the \( \nu_e/\nu_{\mu} \) natural beam contamination. 

|                  | T2K | J-Parc II | NO\( \nu \)A | BNL | PS++ | SPL (3.5) | \( \beta B \) (\( \beta B_{100,100} \)) |
|------------------|-----|-----------|---------------|-----|------|------------|----------------------------------|
| p-driver (MW)    | 0.75 | 4         | 0.8 (2)       | 1   | 4    | 4          | 0.4                             |
| p beam energy (GeV) | 50  | 50        | 120           | 28  | 20   | 2.2 (3.5)  | 1.2-2.2                         |
| \( \langle E(\nu) \rangle \) (GeV) | 0.7 | 0.7       | 2             | 1.5 | 1.6  | 0.27 (0.29) | 0.3 (0.4)                      |
| \( L \) (Km)    | 295 | 295       | 810           | 2540| 732  | 130        | 130                             |
| Off-Axis            | 2°  | 2°        | 0.8°          | -   | -    | -          | -                               |
| \( \nu CC \) (no osc.) (\( Kt^{-1} yr^{-1} \)) | 100 | 500       | 80 (200)      | 11  | 450  | 37 (122)   | 38 (56)                        |
| \( \nu \) contamination (%) | 0.4 | 0.4       | 0.5           | 0.5 | 1.2  | 0.4 (0.7)  | 0                               |
| Detect. Fid. Mass (Kt) | 22.5 | 540       | 30            | 440 | 3.8  | 440        | 440                             |
| Material          | H\(_2\)O | H\(_2\)O | LScint       | H\(_2\)O | LAr  | H\(_2\)O  | H\(_2\)O                       |
| Signal efficiency (%) | 40 | 40        | 24            | 25  | 100  | 70         | 60 (70)                        |
| \( \pi^0/\nu_e \) (\( \pi/\nu_{\mu} \)) (%) | 80 | 80        | 60            | 100 | 0    | 30         | -                              |
| \( \sin^2 2\theta_{13} \times 10^4 \) (90\% C.L.) | 60 | 6         | 38 (24)       | 30  | 50   | 18 (8)     | 7 (2)                          |

In the CERN present layout for a Neutrino Factory (\( \nu F \)) \cite{47} a 4 MW proton beam is accelerated up to 2.2 GeV/c by the Super Conducting Proton Linac (SPL) to produce low energy \( \pi^\prime \)'s in a liquid mercury target, which are collected by a solenoid. Muons produced from the \( \pi \)-decay are then cooled and phase rotated before acceleration through a recirculating Linac system up to 50 GeV/c. These muons of well defined charge and momentum are injected in the \( \mu \) accumulator where they will circulate until they decay, delivering along the two main straight sections two pure \( \nu \) beams whose intensity is expected more than 100 times the one in conventional beams. Both muon signs can be selected. The decay \( \mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu \) (\( \mu^- \rightarrow e^-\overline{\nu}_e\nu_\mu \)) produces a pure well collimated neutrino beam with equal numbers of \( \nu_{\mu}, \nu_e \) (\( \nu_{\mu}, \nu_e \)) and their energy allows to extend the baseline to several thousand kilometers of distance.

The optimal beam energy at the \( \nu F \) will be as large as possible accounting for the difficulties and the technical challenge for the construction of such a muon accelerator complex. \( E_\mu = 50 \) GeV \( (E_\nu \sim 34 \) GeV) represents a limit value for such a new machine. In fact the neutrino flux \( \phi_\nu \) grows like \( E_\nu^3 \) (in the conventional neutrino beams \( \phi_\nu \) is proportional to \( E_\nu \)); the number of charged current neutrino events from the oscillations \( (N_{osc}) \), measured by a detector at a distance \( L \), will be proportional to \( E_\nu \):

\[
N_{osc} \propto \phi_\nu \sigma_\nu \cdot P_{osc} \propto \frac{E_\nu^3}{L^2} \sin^2 \frac{L}{E_\nu} \simeq E_\nu
\]

where \( \sigma_\nu \propto E_\nu \) is the corresponding neutrino interaction cross-section and \( P_{osc} \) is the oscillation probability.

Furthermore, the \( \nu \) intensity can be precisely determined from the measurement of the monochromatic \( \mu \) current circulating in the storage ring (absolute normalization at 1\% level). An accurate
The determination of $\mu$ momentum allows for the measurement of the neutrino energy spectra at the detector site.

The $\nu F$ lends itself naturally to the exploration of neutrino oscillations between $\nu$ flavors with high sensitivity to small mixing angles and small mass differences. The detector should be able to perform both appearance and disappearance experiments, providing lepton identification and charge discrimination which is a tag for the initial flavor and of the oscillation. In particular the search for $\nu_e \rightarrow \nu_\mu$ transitions ("golden channel") appears to be very attractive at $\nu F$, because this transition can be studied in appearance mode looking for $\mu^-$ (appearance of wrong-sign $\mu$) in neutrino beams where the neutrino type that is searched for is totally absent ($\mu^+$ beam in $\nu F$). With a 40 Kt magnetic detector (MINOS like) exposed to both polarity beams and $10^{21}$ muon decays, it will be possible to explore the $\theta_{13}$ angle down to $0.1^\circ$ opening the possibility to measure the $\delta_{CP}$ phase if $|\Delta m_{12}^2| \geq 5 \times 10^{-4}$ eV$^2$ (systematic errors not accounted for) \cite{56,41}.

Unfortunately, as discussed in Section 3, the determination of $(\theta_{13}, \delta_{CP})$ is not free of ambiguities and up to eight different regions of the parameter space can fit the same experimental result. In order to solve these ambiguities, a single experiment on a single neutrino beam is not enough. An optimal combination of $\beta$-beams, SuperBeams and Neutrino Factories has to be considered to deal with the eightfold degeneracy. Several investigations on how to solve this problem have been carried out, as reported in \cite{89} and references therein. As an example the result of such an analysis combining the golden and the silver ($\nu_e \rightarrow \nu_\tau$) $\nu F$ channels with the SPL-SB, taken from reference \cite{60}, is shown in Fig. 14.

More details on the physics performances of a $\nu F$ towards a precision measurement of neutrino oscillation parameters can be found in Refs. \cite{66,47}.

6 Conclusions

Neutrino oscillations are certainly one of the most important discoveries of the recent years. They allow to measure fundamental parameters of the Standard Model, provide the first insight beyond the electroweak scale, play a decisive role in many fields of astrophysics and cosmology and allow to explore $CP$ violation in the leptonic sector.

The precise measurements of the oscillation parameters and of the still unknown parameters $\theta_{13}$, $\text{sign}(\Delta m_{23}^2)$ and $\delta_{CP}$ in the subleading $\nu_\mu \rightarrow \nu_e$ oscillations in particular appear as a must in high energy physics.
Figure 14: The results of a $\chi^2$ fit for $\theta_{13} = 2^\circ$; $\delta_{\text{CP}} = 90^\circ$. Four different combinations of experimental data are presented: a) magnetized iron detector (MID) at a $\nu N$; b) MID plus SPL-SB; c) MID plus hybrid emulsion (HE) at $\nu F$; d) the three detectors together. Notice how in case (d) the eightfold-degeneracy is solved and a good reconstruction of the physical $\theta_{13}, \delta_{\text{CP}}$ values is achieved.
Due to the intrinsic difficulties and complexity of the three flavor neutrino oscillations a single world facility will not probably be sufficient to measure in a firm way all these parameters.

The present generation of neutrino beams at accelerators like NuMI and CNGS can start the exploration of the $\theta_{13}$ angle beyond the Chooz limit. However, power and purity of these conventional neutrino beams, where neutrinos are generated mainly by pion and kaon decays in a wide range of momenta, seem to limit intrinsically the experimental sensitivity.

New high intensity proton accelerator facilities (in the MWatt regime) are required to produce neutrino beams with an intensity and purity much higher than the conventional neutrino beams. Novel concept neutrino beams like BetaBeams and Neutrino Factories, where neutrinos are produced in the decay of radioactive ions and muons respectively, suitable accelerated to a selected momentum, can open new interesting and promising scenarios given the possibility to explore the neutrino oscillation world with high accuracy. These new facilities are under study. They will require a long R&D phase with different time-scales due to the different intrinsic difficulties involved in the projects and in the constructions. The most physics-ambitious road-map is still to be clarified also because no predictions exist for the $\theta_{13}$ parameter, below the Chooz limit $\theta_{13} < 11^\circ$, that drives all the new phenomena.

In the next years SuperBeam facilities, where conventional neutrino beams are improved as flux and purity and tuned to $\nu_\mu \rightarrow \nu_e$ transitions, appear the most suitable. The T2K experiment in Japan at the J-Parc accelerator complex, using Super-Kamiokande as far detector, appears as a reference point in the search, well corroborated by the possibility of a second phase with a more intense beam and a larger detector of about one megaton mass. The option CERN to Gran Sasso neutrino SuperBeam based on improved synchrotron seems to be equivalent to J-Parc II, as far as concerns neutrino fluxes, except for $\nu_e$ level due to the Off-Axis alignment of J-Parc. However, it is mandatory to complement it with a detector in excess of 100 kton mass to exploit its physics potential well beyond the T2K sensitivity.

The SPL-SuperBeam project at CERN, complemented with a megaton water Cerenkov detector, seems to require a too big effort compared with its physics output, even if the 3.5 GeV SPL option greatly improves its discovery potential. A gigantic water Cerenkov detector would be better exploited if fired by a BetaBeam, and it should be stressed that a combination of the SPL-SB with a BetaBeam results to be the most powerful facility proposed before the Neutrino Factories era. Smaller and denser detectors could be only used with BetaBeams of higher energies than that obtainable with the CERN SPS or, in a longer timescale, with the Neutrino Factories. Here, iron calorimeters or liquid argon detectors exceeding 40 Kton of mass, both magnetized in the case of Neutrino Factories, could reach excellent sensitivities in neutrino oscillation physics.
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