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Review Article

Neutrino Oscillations in the Atmospheric Parameter Region: From the Early Experiments to the Present

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The aim of this paper is to provide a historical perspective on the main experimental steps which led to the current picture of neutrino oscillations in the "atmospheric parameter region." In the 1980s a deficit of atmospheric muon neutrinos was observed with the first generation of underground experiments. In the following decade new experiments provided fundamental results which led to the discovery claims in 1998. At the beginning of the new century neutrino beams of medium and high energy became available and several long baseline experiments were performed and added new information to the atmospheric neutrino puzzle. The interpretation of the results of atmospheric and long baseline neutrino experiments was in terms of dominant $\nu_\mu \rightarrow \nu_\tau$ oscillations. Short recollections are made of the SNO solar neutrino measurements, of the results with neutrino telescopes, and of reactor neutrinos to measure $\sin^2\theta_{13}$. Over the years the phenomenological picture improved in completeness and increased in complexity. A short perspective concludes the paper.

1. Introduction

A first hypothesis on neutrino oscillations of the type $\nu \leftrightarrow \overline{\nu}$ was introduced in the 50s by Pontecorvo in analogy with strangeness oscillations in the quark sector [1, 2]. Later the idea was extended to include mixing between mass and flavor eigenstates and transitions between different neutrino flavors [3, 4]. Pontecorvo predicted possible variations of the solar ν flux on Earth due to neutrino oscillations [4].

Experimentally the first indication of a neutrino flux deficit with respect to expectations came from *solar neutrinos*. Since the late 1960s it was observed that the neutrino flux from the sun measured with a chlorine target experiment [5–8] was significantly smaller than that computed with theoretical predictions based on the solar standard model (SSM) [9, 10]. The anomaly was confirmed in the 80s by experiments using gallium (GALLEX [11], SAGE [12, 13], and GNO [14]) and water targets (Kamiokande [15, 16]). The deficit—referred to as the "solar neutrino problem"—was interpreted in different ways, in particular, invoking neutrino oscillations, namely, the conversion in flight of solar ν_e in other neutrino flavors. The final proof of the solar neutrino problem came in 2001 and 2002 with the results of the SNO heavy-water experiment [17, 18]. Measuring the rates of charged current (CC) interactions (sensitive only to ν_e) and of neutral current (NC) interactions (sensitive to all neutrino flavors) it was proved that the deficit existed only for ν_e while the total neutrino flux rate was consistent with the SSM predictions. These results lead to the following conclusions: (i) neutrinos oscillate during their travel toward the Earth, (ii) solar neutrino fluxes are in agreement with the SSM predictions if neutrino oscillations are taken into account, and (iii) it was indirectly proved that neutrino flavors at the detection level are different from those produced at the source. In 2002 the KamLAND experiment [19]—free from the systematics related to solar models—provided a positive indication/evidence for neutrino oscillations in the solar energy sector using artificial $\overline{\nu}_e$ beams from a large number of nuclear reactors. More recently, the Borexino experiment at the Gran Sasso Laboratory confirmed the solar oscillation scenario measuring the flux of the low energy ^{7}Be neutrinos [20, 21].

At another energy scale and much shorter distances, a flux reduction with respect to expectations was observed in the study of atmospheric neutrinos. Incoming high energy primary cosmic rays, protons, or nuclei, interacting with nitrogen and oxygen nuclei in the upper atmosphere, produce pions and kaons, which decay yielding muons and muon neutrinos, in their turn muons decay yielding electrons and muon/electron neutrinos. High energy neutrinos are produced in a spherical layer at ~15 km above ground and they proceed towards the Earth. From simple arguments it follows that the ratio of the numbers of muon to electron neutrinos is ~2 in a limited energy range and $N_{\mu}/N_{\overline{\mu}} \simeq 1$.

The early water Cherenkov detectors IMB [22, 23] and Kamiokande [24–26] reported anomalies in the ratio of muon to electron neutrinos, while the tracking calorimeters NUSEX [27], Fréjus [28, 29], and the final Baksan scintillator detector results [30, 31] determined values in agreement with no oscillations. The ν_{μ}/ν_{e} ratio anomaly was confirmed by the Soudan-2 experiment [32].

At the Neutrino 1998 Conference in Japan the Soudan-2 [33], MACRO [34–37], and Super-Kamiokande (SK) [38] collaborations reported deficits in the muon fluxes from ν_{μ} ($\overline{\nu}_{\mu}$) interactions with respect to Monte Carlo (MC) predictions and distortions in the muon angular distributions; Soudan-2 and Super-Kamiokande also found that the ν_e ($\overline{\nu}_e$) distributions agreed with MC predictions. These features were explained in terms of ν_{μ} oscillations, possibly as $\nu_{\mu} \rightarrow \nu_{\tau}$, while the $\nu_{\mu} \rightarrow \nu_{e}$ channel was excluded as a dominant one.

The atmospheric neutrino flux was computed in the early 1990s [39, 40] and 2000s [41–43]. At low energies, $E_{\nu} \simeq 1$ GeV, the predicted number of neutrinos differed by ~20–30%. At higher energies, $E_{\nu} \geq 10$ GeV, the computations were more reliable and had an estimated systematic uncertainty of about 15%. The predicted relative rates of ν_{μ} and ν_{e} and the shapes of the zenith distributions were affected by lower systematic errors.

Atmospheric neutrino experiments were mainly disappearance experiments, that is, experiments which measured a reduction of the ν_{μ} flux compared with the ν_{e} flux or a depletion in the number of ν_{μ} with the distance from production to detection. The observation of the appearance of some ν_{τ}'s in a ν_{μ} beam would prove the present paradigm of neutrino oscillations.

This paper is organized as follows. In Section 2 the formalism underlying the phenomenon of neutrino oscillations is recalled. Section 3 is devoted to the atmospheric neutrino experiments, separated on a historical basis into "early" experiments, experiments in the "discovery" phase, and precise confirmation accelerator experiments. In Section 4 are discussed the measurements with reactor antineutrinos of the θ_{13} mixing angle and in Section 5 are described the results from the long baseline neutrino oscillation experiments operating in the "atmospheric parameter region" (K2K, NuMi, and CNGS). Section 5.1 is dedicated to the LSND Δm^2 scale and to a discussion of new proposals on the subject of sterile neutrinos. In Section 6 we review existing experimental results which cannot be accommodated in the standard neutrino oscillation framework. In Section 7 are briefly summarized the present experimental efforts to measure neutrino cross sections and kinematical quantities useful for a correct interpretation of the neutrino data. In Section 8 are examined the roles that large neutrino telescopes could have in the framework of neutrino oscillations. We conclude in Section 9 with comments on some important open issues in neutrino physics.

2. Neutrino Oscillations and Masses

The standard model (SM) of particle physics has been experimentally verified to a high degree of accuracy over a broad range of energies and processes [44–49]. The SM cosmology has received confirmations from the Planck experiment [50]. The Higgs particle H^0 was recently discovered at the CERN LHC by the ATLAS and CMS experiments, using mainly the cleanest decays $H^0 \rightarrow \gamma\gamma$ and $H^0 \rightarrow Z^0 Z^0 \rightarrow 4$ charged leptons [51, 52]. The two experiments are now making precise measurements of all the H^0 properties to check if the discovered particle is really the Higgs boson of the SM. In the SM, neutrinos are described as massless left-handed (LH) fields (the opposite for antineutrinos which are right-handed, RH). Each LH neutrino is a component of an SU (2) doublet together with the corresponding charged lepton fields. In case of neutrino mixing and nonzero neutrino masses RH neutrinos (and correspondingly LH antineutrinos) form an SU (2) electroweak singlet with no coupling to SM vector bosons (*sterile neutrinos*).

The existence of neutrino oscillations—and therefore of massive neutrinos—is the first direct and unambiguous evidence for physics beyond the SM. Moreover any theory able to accommodate neutrino masses should provide an explanation for the fermion mass pattern as presently known in the SM, where neutrinos masses are orders of magnitudes smaller than other massive particles (Figure 1). We recall that all particle masses arise from the interactions with the Higgs field. The SM in its present form is not able to predict the mass spectrum illustrated in Figure 1.

The Grand Unified Theory, GUT, is usually obtained assuming the absence of new physics between the electroweak scale and the GUT scale (10^{16} eV). The GUT scale cannot be reached with present or future accelerators. Several theorists consider intermediate energy scales and discuss possible new phenomenological effects [53].

If neutrinos have nonzero masses, the *flavor eigenstates* ν_l ($l = e, \mu, \tau$) are linear combinations of the *mass eigenstates* ν_m ($m = 1, 2, 3$) via the elements of the unitary mixing matrix U_{lm}, usually called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

$$\nu_l = \sum_m U_{lm} \nu_m, \tag{1}$$

where the m index in the summation is extended to the number of mass eigenstates. Neutrino oscillation experiments measure the probability of a ν_l flavor to convert into a $\nu_{l'}$ after a time t from production at some distance $L = ct$ from the source. The corresponding probability can be expressed as

$$P\left(\nu_l \longrightarrow \nu_{l'}\right) = \left|\sum_m U_{l'm} U^{*}_{lm} e^{-iE_m t}\right|^2, \tag{2}$$

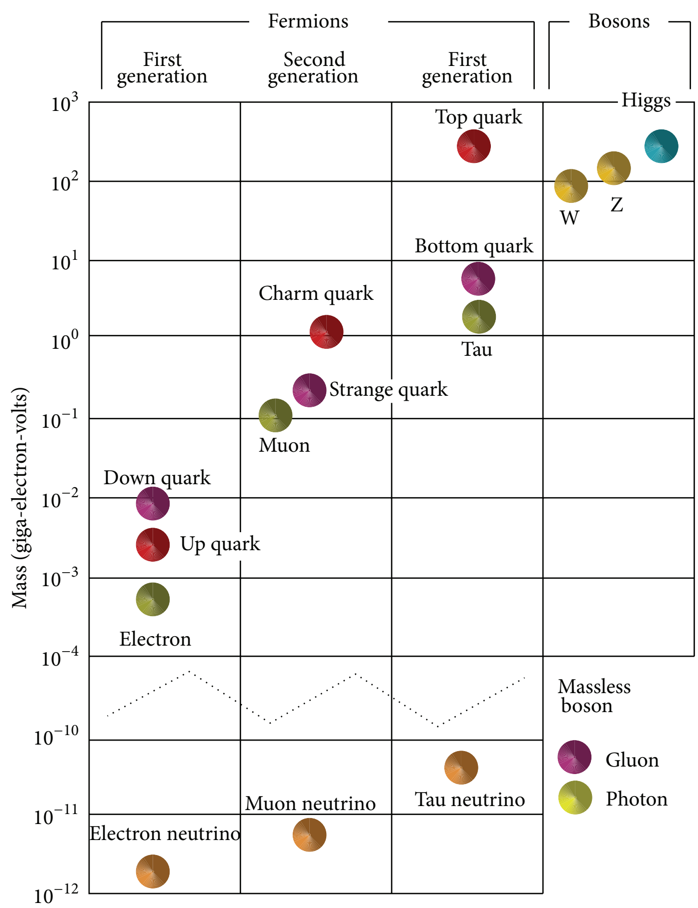


FIGURE 1: Masses of leptons, of quarks, and of the Higgs boson and neutrino mass splittings in the solar and atmospheric sectors. The dots for ν masses indicate mass upper limits. $\sum_1^3 m_\nu \simeq 0.3$ eV gives the upper limit on the sum of neutrino masses from cosmological observations (see text).

where E_m is the energy of the mass eigenstate ν_m. In vacuum, if CPT holds, $P(\nu_l \to \nu_{l'}) = P(\overline{\nu}_l \to \overline{\nu}_{l'})$.

For the neutrinos the mixing matrix U_{lm} is specified by three rotation angles, θ_{23}, θ_{13} , and θ_{12} $(0 \leq \theta_i \leq \pi)$, and three phases δ, α_1, and α_2 $(\delta \geq 0, \alpha_i \leq 2\pi)$. In the conventional parameterization the matrix U_{lm} reads as follows:

$$U \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \operatorname{diag}\left(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1\right) \tag{3}$$

with $s_{12} \equiv \sin\theta_{12}$, $c_{12} \equiv \cos\theta_{12}$ and similarly for the other sines (s_{13}) and cosines (c_{13}, c_{23}, c_{12}). The action of the three rotation matrices is illustrated in Figure 2 with approximate values of the three mixing angles θ_{12}, θ_{13}, and θ_{23}, as presently known [49]. Neutrino oscillations depend on six independent parameters: two mass squared differences, $\Delta m_{21}^2 = m_2^2 - m_1^2$ and $\Delta m_{23}^2 = m_2^2 - m_3^2$, three angles θ_{12}, θ_{13}, and θ_{23}, and the CP-violating phase δ. The (2-3) sector is identified with neutrino oscillations at the atmospheric scale and the (1-2) sector with oscillations at the solar scale; the (1-3) sector concerns $\nu_\mu \to \nu_e$ and, for nuclear reactors, $\overline{\nu}_e$ disappearance. The two phases, α_1 and α_2, do not affect neutrino oscillations but may have physical consequences (e.g., in neutrino-less double beta decay) if neutrinos turn out to be Majorana particles.

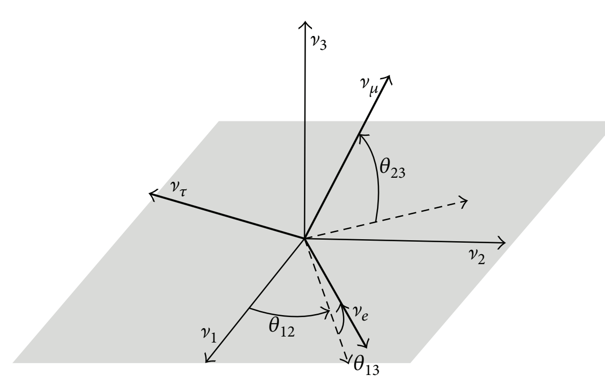


FIGURE 2: Rotations between mass and flavor eigenstates in the 3 families neutrino oscillation scheme ($\theta_{23} \sim 45^\circ$, $\theta_{12} \sim 40^\circ$, and $\theta_{13} < 9^\circ$).

In the approximation of two flavors (ν_μ, ν_τ) and two mass eigenstates (ν_2, ν_3) one can write

$$\begin{aligned}\nu_\mu &= \nu_2 \cos\theta_{23} + \nu_3 \sin\theta_{23},\\ \nu_\tau &= -\nu_2 \sin\theta_{23} + \nu_3 \cos\theta_{23}.\end{aligned} \tag{4}$$

In this case the oscillation probability (2) of a ν_μ beam becomes

$$\begin{aligned}&P\left(\nu_\mu \longrightarrow \nu_\tau\right)\\ &\quad\simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m_{23}^2\left[\mathrm{eV}^2\right] L\,[\mathrm{km}]}{E_\nu\,[\mathrm{GeV}]}\right),\end{aligned} \tag{5}$$

where L is the distance traveled by the neutrino from production to interaction in a detector and E_ν is the neutrino energy. The survival probability for the initial ν_μ is $P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau)$.

In several cases one needs oscillations including three flavors [54].

Since neutrino oscillations are sensitive to (unsigned) neutrino mass differences (5) the present experimental data leave open two possibilities for mass ordering. Since $\Delta m_{21}^2 > 0$ (from solar matter effects measurements), there are two possibilities $m_{\nu_1} < m_{\nu_2} < m_{\nu_3}$ (*normal mass hierarchy*, $\Delta m_{32}^2 > 0$) or $m_{\nu_3} < m_{\nu_1} < m_{\nu_2}$ (*inverted mass hierarchy*, $\Delta m_{32}^2 < 0$).

In matter (e.g., inside the sun) CC coherent scattering of ν_e with atomic electrons changes the weak potential, a phenomenon known as the Wolfenstein-Mikheyev-Smirnov (MSW) effect [55, 56].

The oscillation parameters are modified according to

$$\begin{aligned}\sin^2 2\theta_M &= \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2},\\ \Delta m_M^2 &= \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2},\end{aligned} \tag{6}$$

where $x = 2\sqrt{2} N_e G_F E_\nu / \Delta m^2$, with N_e the electron density in matter and G_F the Fermi constant.

We now recall the existing limits on neutrino masses, on the number of light neutrinos, and on neutrino lifetime obtained from searches at accelerators and from observational cosmology [41–43, 57, 58].

Direct Measurements of Neutrino Masses. Many direct measurements were and are being performed using mainly tritium decay, $^3H \rightarrow {}^3H^+ + e^- + \overline{\nu}_e$, measuring, with magnetic spectrometers of ever increasing precision, the electron spectrum near its kinematical limit where the number of events is small, $\sim 10^{-3}$ times of the whole sample. The present best limit is $m(\overline{\nu}_e) < 2$ eV (95% CL) [49]. Notice that in direct searches the upper limits correspond to a weighted average of the neutrino mass contributing to a given flavor since the measured quantity is

$$m_{\nu_l}^2 = \sum_{m=1}^{3} \left|U_{lm}\right|^2 m_{\nu_m}^2. \tag{7}$$

Limits on ν_μ and ν_τ masses were obtained at accelerators using muon and tau decays which yielded $m(\nu_\mu) < 0.19$ MeV, $m(\nu_\tau) < 18$ MeV [49]. The last limit comes from the combination of results from different experiments, mainly at LEP. In these experiments the most sensitive conditions are when the τ decays into many charged pions [59].

Neutrino-less double-β decay searches provide limits on the effective Majorana mass $\langle m_{\beta\beta}\rangle = |\sum_{m=1}^{3} U_{1m}^2 m_{\nu_m}|$. The present best upper limit ranges from 0.19 eV to 0.68 eV depending on the nuclear matrix calculation used [60]. It is worth noting that the discovery of the Majorana nature of neutrinos would have a deep impact on the general framework of the SM in which all fermions obey the Dirac equation: neutrinos would be the only exceptions.

Massive ν's and Cosmology. Massive stable neutrinos contribute to the overall energy density of the universe. In particular if $\sum m_\nu < 1$ eV the neutrinos would affect the clustering of galaxies at relatively large cosmological scales. A limit on $\sum m_\nu < 0.3$ eV was obtained by the Planck satellite collaboration [50].

Number N_ν of Light Neutrino Types. The most precise measurements of the number of light "active" neutrinos (i.e., neutrinos with electroweak couplings) come from the four LEP experiments. The combined result is $N_\nu = 2.984 \pm 0.008$ [49].

The density of radiation in the universe, besides photons, is usually parametrized by the effective neutrino number N_{eff}. In the standard model of cosmology, $N_{\text{eff}} = 3.046$.

The recent Planck observations provide no compelling evidence for additional neutrino species. Combining Planck, WMAP polarization, and the long baseline experiments gives (95% CL) [50, 61]

$$N_{\text{eff}} = 3.36^{+0.68}_{-0.04}. \tag{8}$$

Neutrino Lifetime. The indications from experiments and from cosmology are that neutrinos are either stable or long lived [62]. Specific experiments which searched for radiative solar neutrino decays during total solar eclipses yielded $\tau_\nu > 10 - 10^9$ s depending on the ν_1 mass [63].

3. Atmospheric Neutrino Experiments

The main sources of atmospheric neutrinos are the decays of charged mesons (π and K) produced in the primary cosmic ray interactions with atmospheric atomic nuclei. Mesons in turn decay into μ and ν_μ. At low energies muon decay gives rise to electron, electron neutrinos, and muon neutrinos:

$$\mu^- \longrightarrow e^- \overline{\nu}_e \nu_\mu, \qquad \mu^+ \longrightarrow e^+ \nu_e \overline{\nu}_\mu \tag{9}$$

with fluxes $\Phi(\nu_\mu) \sim \Phi(\overline{\nu}_\mu) \sim 2\Phi(\nu_e)$ and flux ratios $\Phi(\nu_e)/\Phi(\overline{\nu}_e) \sim \Phi(\mu^+)/\Phi(\mu^-)$. In this energy region the total atmospheric neutrino flux is of the order of 0.1 cm^{-2} s^{-1} and the energy spectrum can be approximated with a power law $\Phi_\nu \sim E_\nu^{-2}$. The zenith angle distribution is asymmetric since at low energy the primary CR flux depends on the geomagnetic location and so does the neutrino flux.

At high energy muon decay can be neglected and meson decay remains the dominant atmospheric neutrino source. The neutrino flux steepens and it becomes asymptotically steeper than the primary flux ($\sim E_{\nu}^{-3.7}$). In this case the zenith angle distribution is symmetric around the horizontal direction where the neutrino flux is maximum since the path length in atmosphere is maximum and hence the probability of mesons to decay into neutrinos is symmetric.

Atmospheric neutrinos are well suited to study neutrino oscillations, since they have energies from a fraction of a GeV up to more than 100 GeV and they may travel distances L from few tens of km up to 13000 km; thus the ratio L/E_{ν} in (5) ranges from ~1 km/GeV to ~10^5 km/GeV. In particular they cover regions for Δm_{23}^2 of the order of $10^{-3} \div 10^{-2}$ eV^2.

Atmospheric neutrino oscillations can be studied by means of three observables.

(i) First, one can measure the ratio of the measured number of ν_{μ} events over the predicted one. In order to reduce the systematic error related to the limited knowledge of the absolute flux normalization, one can use the double ratio

$$R = \frac{\left(N_{\nu_{\mu}}/N_{\nu_e}\right)_{\text{obs}}}{\left(N_{\nu_{\mu}}/N_{\nu_e}\right)_{\text{MC}}} \tag{10}$$

in which the ν_{μ} flux is referred to the ν_e flux.

(ii) One may consider that there are two identical sources for a single detector: a near one (downgoing neutrinos) and a far one (upgoing neutrinos) which correspond, respectively, to a short and to a large baseline L. For relatively high energy neutrinos ($E_{\nu} > 10$ GeV) the outgoing muon preserves with good accuracy the original neutrino direction $\langle\theta_{\text{scattering}}\rangle \simeq 10^{\circ}$ and the path length can be measured. Assuming $\Delta m^2 \sim 10^{-3}$ eV^2, from (5), $P(\nu_{\mu} \rightarrow \nu_{\mu}) \simeq 0$ for downgoing neutrinos and $P(\nu_{\mu} \rightarrow \nu_{\mu}) \simeq 1 - \sin^2 2\theta_{23}/2$ for upgoing neutrinos. Therefore the measurement of the flux ratio

$$\frac{N_{\text{Up}}}{N_{\text{Down}}} \simeq 1 - \frac{\sin^2 2\theta_{23}}{2} \tag{11}$$

can directly provide information of the mixing angle θ_{23}.

(iii) A third approach is to measure the ν_{μ} flux reduction as a function of the baseline L (and therefore of the zenith angle). In this case one may explore the argument of the second sinusoidal term in (5) (which was averaged to ~1/2 in the previous case).

3.1. Early Experiments. The first experimental information on atmospheric neutrinos came in the 1960s and 1970s from two small detectors located at great depths in South Africa (KGF) [64] and in India (CWI) [65], then followed the experiments Baksan, IMB, Kamiokande, NUSEX, and Fréjus.

For all these studies the main motivation was the search for proton decay and atmospheric neutrinos were a background; only later the search for neutrino oscillations became an interesting possibility.

The *Baksan* Underground Scintillation Telescope is located at a depth of 850 m.w.e. in the Caucasus region. It is made of liquid scintillation counters placed to form a parallelepiped of 17 m × 17 m × 11 m. The selection of muon events produced by up-through-going neutrinos is made with time of flight methods. In the early data the zenith angle distribution deviated from expectations and seemed to agree with oscillations [30]. Later they considered also the absolute number of events and there is an agreement with Monte Carlo predictions; the ratio data/MC is 1.00 ± 0.04 (stat.) ± 0.08 (syst.) [31].

The *IMB* detector was an 8000 t cylindrical water box placed in the Morton salt mine in Ohio, 1750 m.w.e. deep underground [22, 23]. The Cherenkov light produced by relativistic charged particles passing in the water was detected by photomultipliers installed in the tank walls. The detector started operation in 1982 and was upgraded by increasing the size of the photomultipliers.

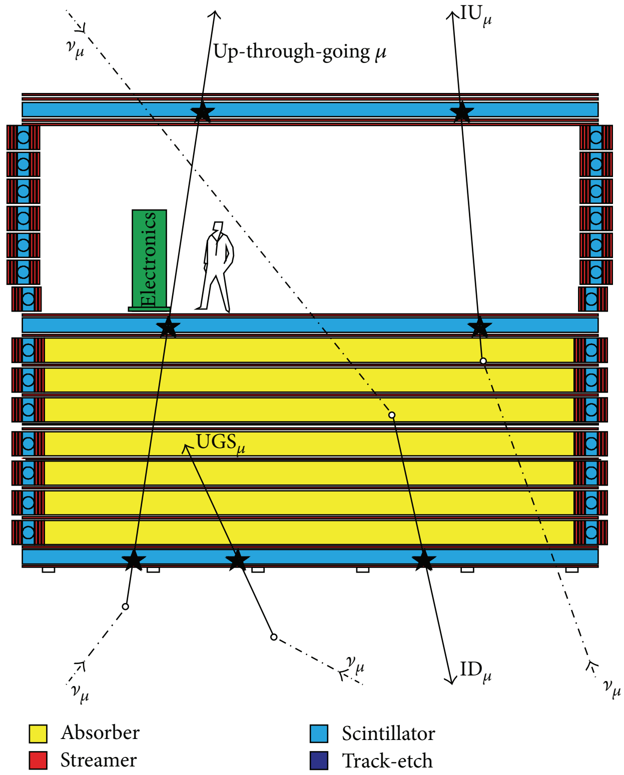
The *Kamiokande* cylindrical detector had a water mass of 3000 t seen by 1000 large PMTs of 50 cm diameter [24–26, 49]. It was installed in the Kamioka mine in Japan at a depth of 2700 m.w.e. It started operations in 1983 and had several upgrades, known as Kamiokande I, II, and III.

The *NUSEX* detector was a fine granularity detector with a total mass of 150 t, placed in the Mont Blanc tunnel between Italy and France at a depth of 4800 m.w.e. The detector was made of horizontal 3 mm iron plates interleaved with layers of limited streamer tubes [27].

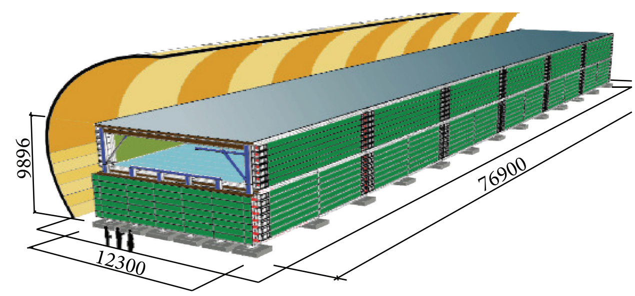
At the same depth was located the 912 t *Fréjus* detector. It was made of pairs of vertical iron slabs each 1.5 mm thick interleaved with pairs of planes of flash tubes; their trigger was made with Geiger tube layers inserted every 8 layers of flash tubes [28, 29].

The early water Cherenkov detectors and the tracking calorimeters detected ν_{μ} and ν_e charged current interactions. The results were expressed in terms of the double ratio $R' = R_{\text{obs}}/R_{\text{MC}}$, where $R_{\text{obs}}=(N_{\nu_{\mu}}/N_{\nu_e})_{\text{obs}}$ is the ratio of observed muon and electron events and R_{MC} is the same ratio for Monte Carlo (MC) events. In R' many systematic uncertainties cancel. The double ratios from IMB and Kamiokande were smaller than expectations, while for NUSEX and Fréjus they were in agreement with expectations without oscillations. The IMB collaboration concluded that "however the magnitude of the deviation is not sufficient to require neutrino oscillations to explain our data." The overall spectra and total number of interactions were in agreement with predictions. Furthermore there was no correlation of deficit with energy or angle [22, 23]. The Kamiokande experiment obtained indications for ν_{μ} oscillations with maximal mixing and $\Delta m_{23}^2 = 16 \times 10^{-3}$ eV^2, a value considerably larger than the present best value $(2.3 - 2.4) \times 10^{-3}$ eV^2 [24–26].

3.2. The Discovery of Atmospheric Neutrino Oscillations. At the Neutrino 1998 Conference, Soudan-2, MACRO, and



(a)



(b)

FIGURE 3: Cross section (a) and global view (b) of the MACRO detector. In the left figure are also shown the observed neutrino-induced event topologies.

Super-Kamiokande (SK) presented strong indications in favor of atmospheric neutrino oscillations [33–38]. After 1998 several additional results were presented [66–70].

The Soudan-2 experiment [69, 70] used a modular fine grained tracking and showering calorimeter of 963 t, located at a depth of 2100 m.w.e. in the Soudan Gold mine in Minnesota. The bulk of the target was 1.6 mm thick corrugated steel sheets interleaved with drift tubes. In the final analysis fully contained high resolution events, consisting mostly of quasi-elastic neutrino interactions were used. The data were compared with the Bartol Monte Carlo neutrino flux [39]. The double ratio $R' = (N_\mu/N_e)_{\mathrm{DATA}}/(N_\mu/N_e)_{\mathrm{MC}}$ integrated over the zenith angle was (0.68 ± 0.11), consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing and $\Delta m^2_{23} = 5.2 \times 10^{-3}\ \mathrm{eV}^2$ (Figure 6(b)). The experiment ended in 2001.

The MACRO experiment operated at the Gran Sasso underground Lab (3800 m.w.e.) from 1989 to 2000. Figure 3 shows a global view and a cross section of the detector. It used 3 different subdetectors: scintillation counters, limited streamer tubes, and nuclear track detectors [71]. Up-through-going muons with $E_\mu > 1$ GeV came from CC interactions in the rock below the detector and had $\langle E_\nu \rangle \sim 50$ GeV. The angular distribution of these muons is highly sensitive to neutrino oscillations as can be seen in Figure 4.

The MC scale uncertainties on the expected muon flux arising from the neutrino flux, cross section, and muon propagation were estimated at ~17%. In Figure 5(a) the zenith angle distribution is compared with MC predictions. A measurement of the up-through-going muon energies was made via multiple Coulomb scattering in the dense structure of the apparatus using the streamer tubes in "drift mode" [72, 73]. The ratios Data/$\mathrm{MC}_{\text{no-osc}}$ as a function

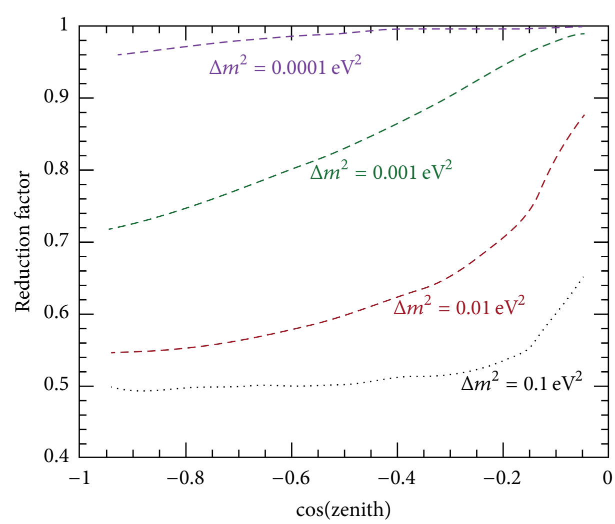
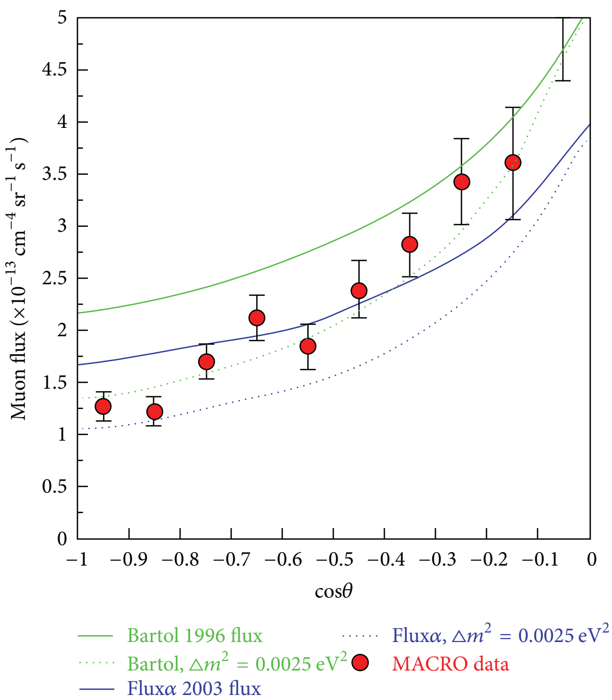
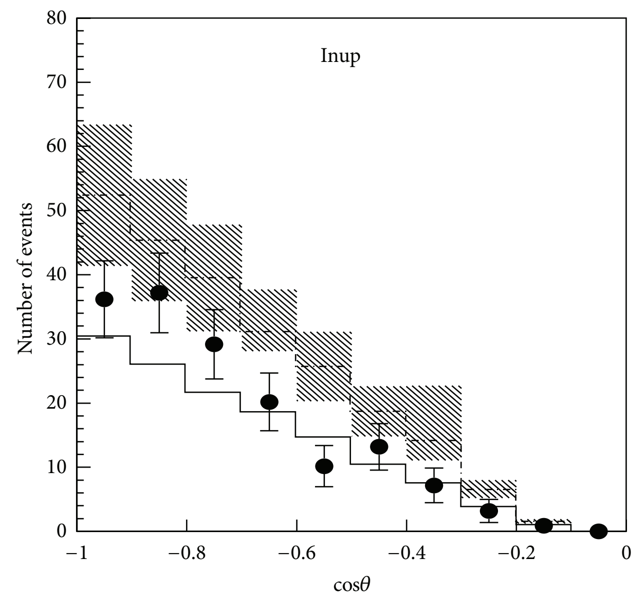


FIGURE 4: Reduction factor in the number of upgoing muons for different Δm^2_{23} values for a muon detection threshold of 1 GeV (MC studies). Note the shape dependence vs the Δm^2_{23} values.



(a)



(b)

FIGURE 5: (a) MACRO up-through-going muons compared with oscillated and nonoscillated predictions of different MCs [68]. (b) Measured zenith distributions for the IU low energy events. The black points are data; the shaded region is the MC predictions with no oscillations. The full line is for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with maximal mixing and $\Delta m^2 = 2.3 \times 10^{-3}$ eV^2.

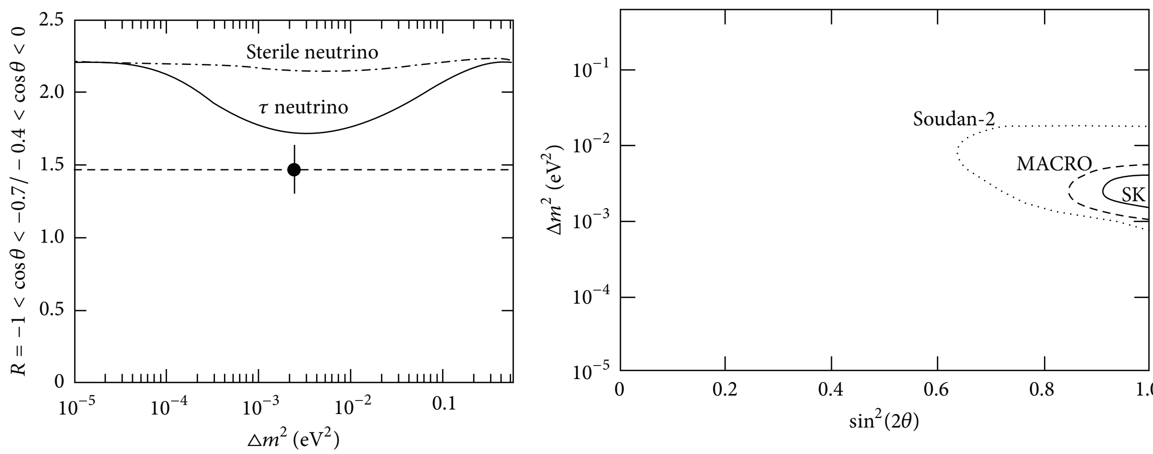
of $\log_{10}(L/E_\nu)$ give additional information on neutrino oscillations.

Low energy neutrino events $\langle E_\nu \rangle \simeq$ 2-3 GeV (Figure 5(b)) included (i) semicontained upgoing muons (IU) from ν_μ interactions inside the lower part of the apparatus, (ii) upgoing muons stopping in the detector (UGS) due to external ν_μ interactions, and (iii) semicontained downgoing muons (ID) originating from ν_μ interactions in the lower detector. The lack of time information prevented distinguishing between ID and UGS samples. In Figure 5(b) the number of IU events and the angular distributions are compared with MC predictions. The data show a uniform deficit over the whole angular distribution with respect to MC.

In 1998 MACRO results were consistent with neutrino oscillations, with $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and maximal mixing [34–37]. In the final analysis [68] three different ratios were considered in order to reduce systematic uncertainties and MC prediction effects: (1) the ratio $R_1 = N_{\text{vert}}/N_{\text{hor}}$ of vertical over horizontal neutrino events in the up-through-going data sample; (2) the ratio $R_2 = N_{\text{low}}/N_{\text{high}}$ of low energy over high energy neutrino events; (3) the double ratio $R_3 = (\text{Data}/\text{MC})_{\text{IU}}/(\text{Data}/\text{MC})_{\text{ID+UGS}}$ for the semicontained data sample. Fitting the three ratios to the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis MACRO obtained $\sin^2 2\theta = 1$ and $|\Delta m^2_{23}| = 2.3 \times 10^{-3}$ eV^2. In Figure 6(b) the 90% CL allowed parameter region is shown. The addition of the absolute flux information in the global fit increased the statistical significance of the result to the 6σ level.

Since ν_μ and ν_τ interactions with matter share the same weak potential whereas sterile neutrinos do not experience weak interactions, a possibility to discriminate between $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{\text{sterile}}$ oscillations is to study the neutrino flux emerging from different matter amounts. That was realized by comparing events near the vertical direction with the event number near the horizontal direction [74, 75]. The angular regions were chosen by MC methods to obtain the best discrimination (Figure 6(a)). In the ratio most of the uncertainties cancel. MACRO excluded at the 99.8% CL the $\nu_\mu \leftrightarrow \nu_{\text{sterile}}$ oscillations compared to the $\nu_\mu \leftrightarrow \nu_\tau$ channel [76].

The Super-Kamiokande *(SK)* detector is a large cylindrical water Cherenkov detector containing 50 kt of water, with a fiducial mass of 22.5 kt. The experiment is still taking data. The Cherenkov light is seen by 50 cm diameter inner-facing phototubes (PMTs) (Figure 7). The 2 m thick outer layer of water acts as an anticoincidence using smaller outward facing PMTs. The detector is located in the Kamioka mine, Japan. The experiment was originally planned mainly to search for proton decay. Atmospheric neutrinos are detected through the Cherenkov light generated by the charged particles produced in neutrino CC interactions in the water. The large detector mass allows defining a fiducial volume large enough to collect good samples of *fully contained* events (FC) up to ~5 GeV. The events are further subdivided into *sub-GeV* and *multi-GeV* events, with energies below and above 1.33 GeV. The *partially contained* events (PC) are CC interactions where the vertex is within the fiducial volume and a charged



(a) (b)

Figure 6: (a) The MACRO ratio between the data in two angular bins (black point on gray line) and comparison with MC $\nu_\mu \leftrightarrow \nu_{\text{sterile}}$ oscillations. (b) 90% CL allowed regions for the $\nu_\mu \leftrightarrow \nu_\tau$ oscillations up to year 2004.

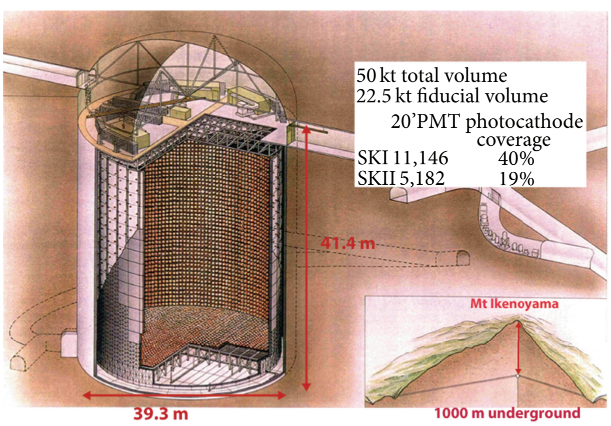


Figure 7: Global view of the SK detector.

particle, a muon, exits the detector without releasing all of its energy (Figure 8). In this case the light pattern is a filled circle. For these events the energy resolution is worse than that for FC interactions. Upward-going muons (UPMU), produced by upgoing neutrinos coming from interactions in the rock, are subdivided into stopping muons ($\langle E_\nu \rangle \sim 7$ GeV) and up-through-going muons (with $\langle E_\nu \rangle \sim 70 \div 80$ GeV) if they stop or not in the detector.

Particle identification in SK is performed using likelihood functions to parameterize the sharpness of the Cherenkov rings, which are more diffuse for electrons than for muons. The algorithms discriminate the two flavors with high purity. The zenith angle distributions for e-like and μ-like sub-GeV and multi-GeV events, for PC events and upward-going or stopping muons, are shown in Figure 8.

At the time of Neutrino '98 Conference the values for the double ratio R' previously defined were $0.658 \pm 0.016_{\text{stat}} \pm 0.035_{\text{sys}}$ for the sub-GeV sample and $0.702 \pm 0.031_{\text{stat}} \pm 0.101_{\text{sys}}$ for multi-GeV [66, 67].

SK uses a selected sample of events with good resolution in L/E_ν to search for the dip in the oscillation pattern expected when the argument of the second sine-squared term in (5) is $\pi/2$. The dip is observed at $L/E_\nu \simeq 500$ km/GeV (Figure 9). These results favor $\nu_\mu \rightarrow \nu_\tau$ oscillations and provide a further constraint on $|\Delta m^2_{23}|$. Other models that could explain the zenith angle and energy dependent deficit of the atmospheric muon neutrinos are disfavored since they do not predict any dip in the L/E_ν distribution. For $\nu_\mu \leftrightarrow \nu_\tau$ oscillations the best fit yields maximal mixing and $|\Delta m^2_{23}| = 2.3 \times 10^{-3}\ \text{eV}^2$ [66, 67].

Several tests were performed by the SK experimenters and by several groups of phenomenologists on the $\nu_\mu \leftrightarrow \nu_{\text{sterile}}$ possibility [78], on the possible LVI [79, 80], and so forth. SK made also a variety of fits of the SK I, II III, and IV data sets in the 3-flavor oscillation scenario obtained at 90% CL: $1.7 < \Delta m^2_{23} < 2.7 \cdot 10^{-3}\ \text{eV}^2$ and $0.41 < \sin^2\theta_{23} < 0.58$. In the 3-flavor analysis there is no preference for normal or inverted neutrino mass hierarchy [78, 81].

SK also searches for $\nu_\mu \rightarrow \nu_\tau$ appearance studying several event-related variables with a neural network. Despite the complicated ν_τ event topology and the high background they claimed a 2.4 σ significance [82], recently updated with SK I + II + III data to 3.8σ.

Super-Kamiokande has the largest statistics in different energy regions, all in agreement with atmospheric ν_μ oscillations. The SK main results are summarized in Table 2 and Figures 8, 9, 10, and 11(b). With more data and a 3-flavor analysis SK may be able to find if θ_{23} is smaller than its maximum and to determine in which octant it lies [83, 84].

Several proposals were made for the Gran Sasso Lab, for example, the MONOLITH proposal for a massive magnetized iron detector for atmospheric neutrinos [85]. For the future there should be the INO proposal for an India-based Neutrino Observatory [86].

4. The Mixing Angle θ_{13}

In the limit $\theta_{13} \rightarrow 0$, atmospheric and solar neutrino oscillations decouple and can be analyzed separately in the 2-neutrino-flavor approximation.

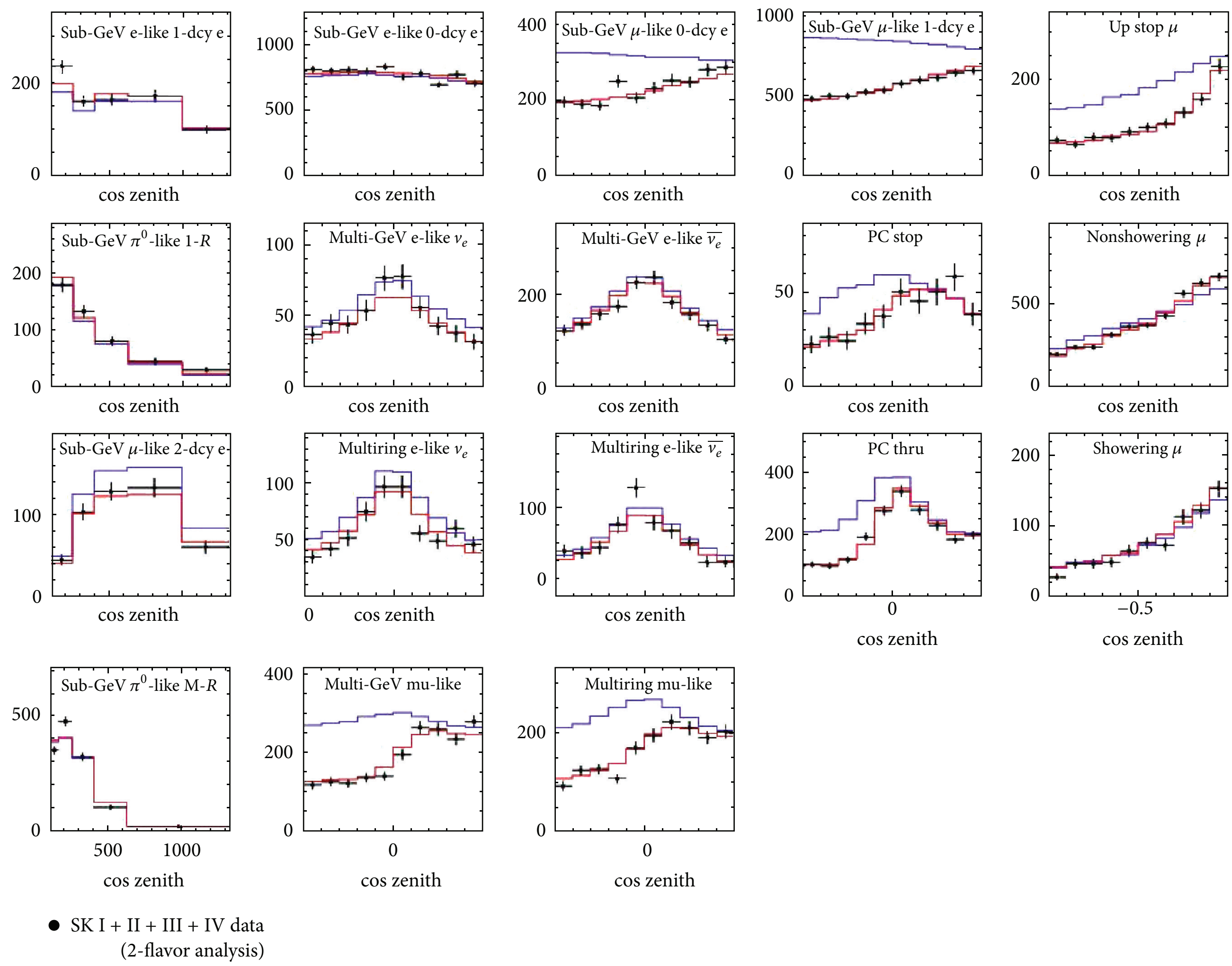


Figure 8: Zenith angle distributions from the SK detector (data from SK I + SK II + SK III) [77].

The knowledge of θ_{13} is very important since it is strictly connected with the CP-violating δ phase in the matrix element, $U_{e3} = \sin\theta_{13}e^{i\delta}$. Its precise knowledge is decisive for further experiments.

The first two $\overline{\nu}_e$ experiments at nuclear reactors, which attempted to measure θ_{13} in disappearance mode, were CHOOZ and Palo Verde [87, 88]. No evidence for $\overline{\nu}_e$ disappearance was found. They obtained limits for $\overline{\nu}_e \rightarrow \overline{\nu}_\mu$ at the level of $\Delta m^2 > 10^{-3}$ eV^2 for $\sin^2 2\theta_{13} > 0.1$.

Recently 3 experiments, Daya Bay, Double Chooz, and RENO, each using several nuclear reactors, measured the neutrino oscillation angle θ_{13}, the last parameter needed to really understand the phenomenon of neutrino oscillations. The nuclear reactors are of the latest French-German design (EPR of generation 3 or 3$^+$) [89–95]. In Table 1 the most relevant parameters of neutrino reactor experiments are given:

(i) 6 reactors in China (Exp. Daya Bay): $\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) $\pm$ 0.005 (syst) [89–91],

(ii) 2 reactors in France (Exp. Double Chooz): $\sin^2 2\theta_{13} = 0.0097 \pm 0.034$ (stat) $\pm$ 0.0034 (syst) [92, 93],

(iii) 6 reactors in Republic of Korea (Exp. Reno): $\sin^2 2\theta_{13} = 0.100 \pm 0.010$ (stat) $\pm$ 0.015 (syst) [94, 95].

These experiments used refined detectors. They obtained important results taking advantage of the very large fluxes of low energy $\overline{\nu}_e$ from the power reactors. θ_{13} was found to be small but not zero: the average value is $\sin^2\theta_{13} = 0.098 \pm 0.013$ [49]. T2K confirmed the measurement [96]. The measured value of θ_{13} opens the possibility of performing many types of precision measurements in the leptonic sector [97–101].

5. Long Baseline High Energy ν Oscillation Experiments

Long baseline accelerator experiments provide independent measurements of oscillation parameters. Some of these experiments may be complementary to reactor experiments. By combining the results of two such experiments at different baselines, the sign of Δm^2_{23} could be determined.

Table 1: Nuclear reactor experiments Daya Bay, Reno, and Double Chooz. For each experiment the location, the number of nuclear reactors, the overall thermal power, the near/far detector distances, and the approximate depth of near/far detectors are given. Note that Daya Bay has two separate reactor core sites and therefore two near/far distances.

Experiment	Location	Number of reactors	Total thermal power (GW)	Distances near/far (m)	Average depth near/far (mwe)
Daya Bay	China	6	17.4	360/1985 500/1615	260/910
Reno	Republic of Korea	6	17.3	290/1380	120/450
Double Chooz	France	2	8.5	410/1050	120/300

Table 2: Main parameters and results of some relevant atmospheric neutrino experiments.

Experiment	Fiducial mass (kt)	Detection technique	Δm^2_{23} (best fit) ($\times 10^{-3}$ eV^2)	Mixing angle θ_{23}
Baksan	—	Scintillators	No value	Angular distrib. anomaly
Kamiokande	1.04–1.35	Water Cherenkov	16[a]	Maximal[a]
IMB	3.3	Water Cherenkov	—	—
Soudan-2	0.96	Drift tubes	5.2[a]	Maximal[a]
MACRO	5	Liquid scintillators and streamer tubes	2.3[a]	Maximal[a]
Super-K	22.5	Water Cherenkov	2.2–2.6[b]	$0.95 < \sin^2 2\theta^{b}_{23}$

[a]2-flavor analysis, [b]3-flavor analysis.

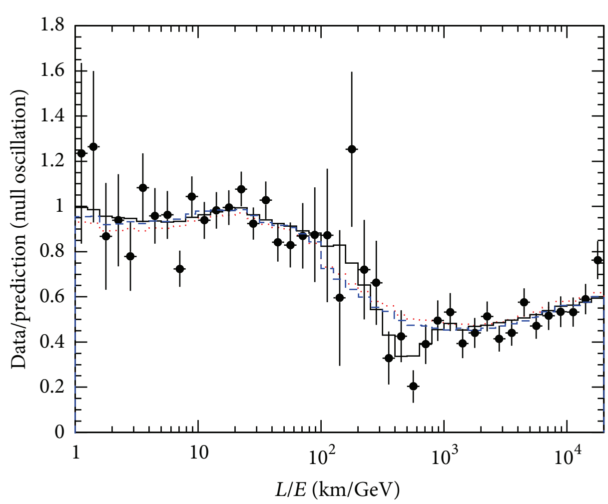


Figure 9: Data/MC ratio versus L/E_ν (black points) for SK. The red solid line is the MC expectation with $|\Delta m^2_{23}| = 2.5\ 10^{-3}$ eV^2 and maximal mixing [66, 67].

High energy neutrino beams are produced accelerating protons up to tens of GeV and impinging them on a target. The produced secondaries are momentum-selected by a series of lensing devices ("*horns*") which focus them into a parallel beam in an evacuated decay tunnel of ~1 km length. Table 2 summarizes the main parameters of atmospheric ν experiments. In Table 3 the main parameters of past, present, and possible future long-baseline neutrino oscillation experiments are listed.

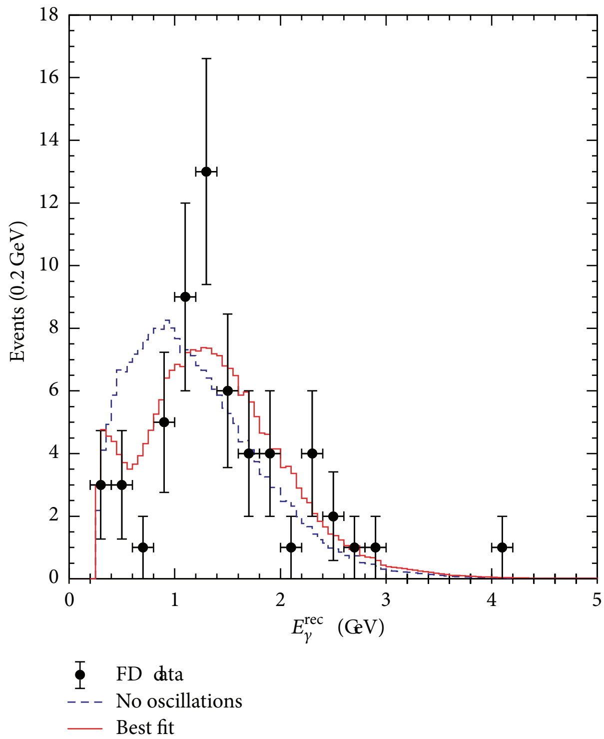
The *K2K* experiment confirmed the atmospheric muon neutrino oscillation picture [102, 103]. Near detectors located at ~300 m from the target measured the energy spectrum and the flux normalization. In total 112 beam-originated neutrino events were observed in the SK fiducial volume with an expectation of $158.1^{+9.2}_{-8.6}$ events for no oscillations, providing a statistical significance against no oscillations of ~4.3σ. A subsample of 58 one-ring events was assumed to be quasi-elastic interactions and energy reconstructed using the known beam direction. The energy spectrum in Figure 10(a) shows the energy-dependent distortion expected from oscillations. In a 2-flavor oscillation scenario, the best-fit value yielded $|\Delta m^2_{23}| = 2.8 \times 10^{-3}$ eV^2 and maximal mixing. The K2K allowed region for the oscillation parameters is consistent with that from atmospheric neutrino data (Figure 10(b)).

The *NuMi 3.7* GeV *energy neutrino beam* uses neutrinos produced by the Fermilab Main Injector, a 120 GeV proton synchrotron capable of accelerating 5×10^{13} protons with a cycle time of 1.9 s. The flavor composition of the beam is 98.7% ($\nu_\mu + \overline{\nu}_\mu$), with a relatively large fraction of $\overline{\nu}_\mu$.

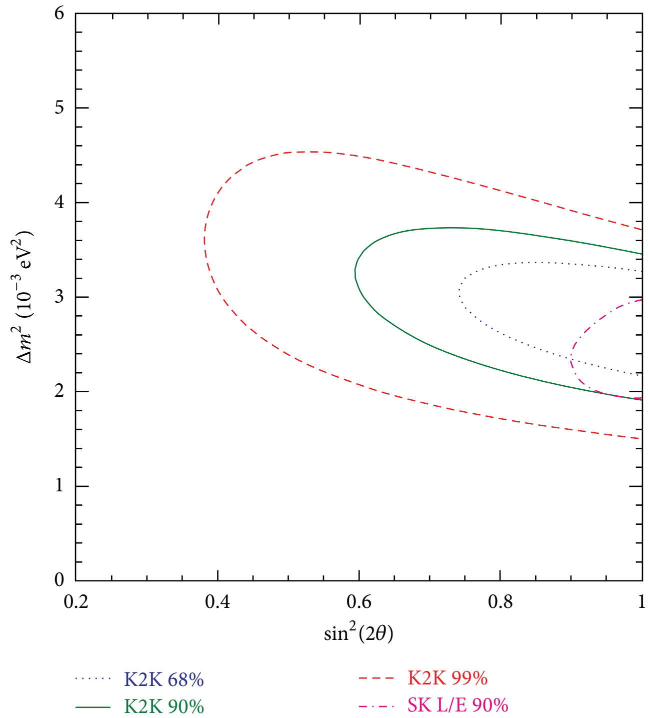
MINOS on the NuMi beam uses a near detector at Fermilab and a far detector at the Soudan mine site, 735 km away, at a depth of 2090 m.w.e. Both are iron-scintillator sandwich calorimeters with a toroidal magnetic field in the octogonal iron plates, interleaved with active planes of long scintillator strips providing both calorimetric and tracking information. The far detector (Figure 11(b)) has a total mass of 5400 t. The magnetic field is 1.3 T. The near detector, with a total mass of 920 tons, is installed 250 m downstream from the end of the decay pipe.

MINOS confirmed the atmospheric neutrino oscillation picture with improved accuracy in Δm^2_{23}, not in angle (Figure 11(a)). It rejects neutrino decay [106] and decoherence [107]. In the $\nu_\mu \leftrightarrow \nu_\tau$ scheme it obtains $|\Delta m^2_{23}| = (2.41 \pm 0.10)\times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} \gtrsim 0.890$ (90% CL) [104, 108, 109].

The CERN to Gran Sasso Neutrino Beam (CNGS). The 400 GeV proton beam from the CERN-SPS is transported to an underground target. Secondary pions and kaons are focused into a parallel beam and decay into μ and ν_μ. The remaining hadrons are absorbed in the hadron stopper.

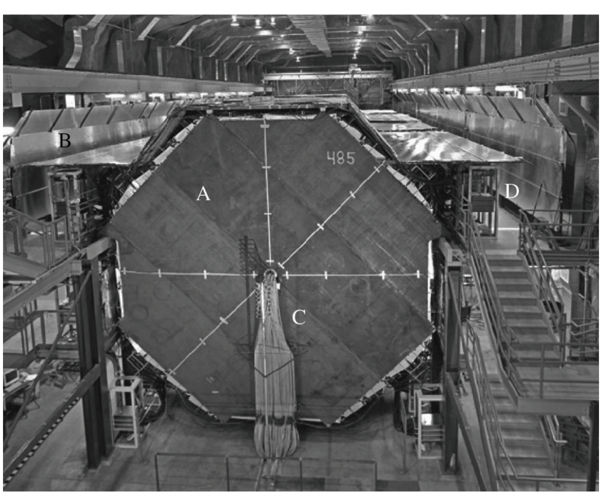


(a)

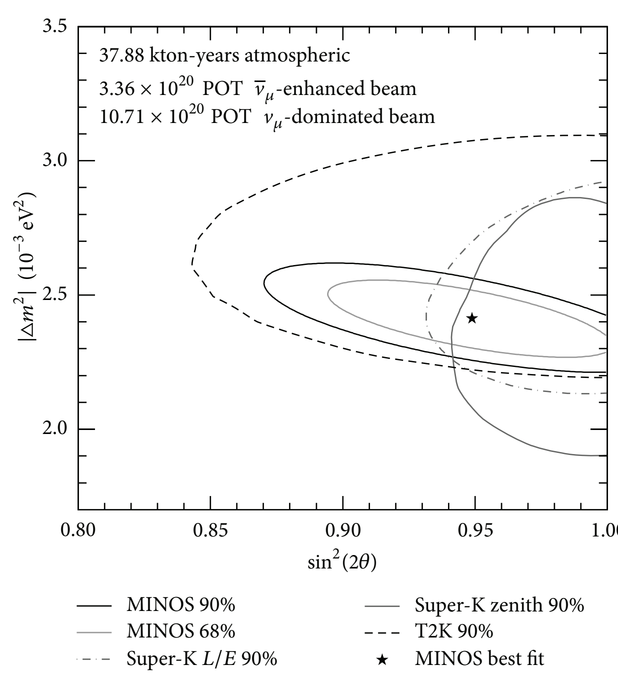


(b)

FIGURE 10: (a) Reconstructed energy spectrum for 58 one-ring events detected by K2K. The dashed blue line is for MC no oscillations; solid red line is the MC oscillation best fit. Both MC histograms are normalized to the data. (b) Comparison of K2K results with the SK atmospheric neutrino measurement [102, 103].



(a)

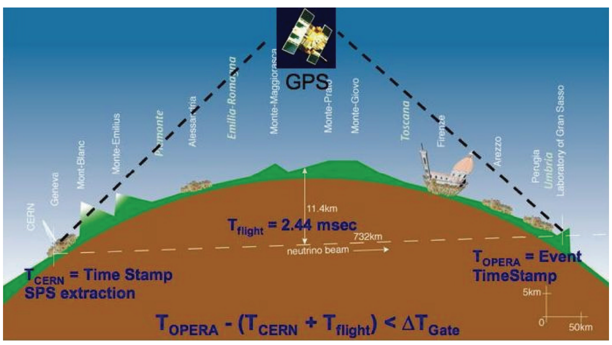


(b)

FIGURE 11: (a) Photograph of the MINOS far detector: "A" indicates the magnetized iron sheets, "C" is the electric coil, and "B" is an anticoincidence scintillator system. (b) Δm_{23}^2 versus $\sin^2 2\theta_{23}$ for ν_μ oscillations measured by MINOS [104] and other experiments [105].

Table 3: Main parameters of past, present, and future long-baseline neutrino oscillation experiments.

Experiment	Run	E_ν	Baseline (km)	Technique	Far detector fiducial mass (kt)	Near detector fiducial mass (t)
K2K	1999–2004	1.0	250	Water Cherenkov	22.5	1000
MINOS	2005-	3.3	735	Steel + scintillators	4	30
OPERA	2008-	17	732	Nuclear emulsions	1.25	—
ICARUS	2010–2013	17	732	LAr	0.48	—
T2K	2010-	0.6	295	Water Cherenkov	22.5	6
NOνA	2013-	2.0	810	Liquid scintillators	15	220
T2HK	2020?-	0.6	295	Water Cherenkov	540	?



GPS time stamp resolution ~ 100 ns

Figure 12: Sketch of the 730 km neutrino path from CERN to Gran Sasso and the GPS selection of events.

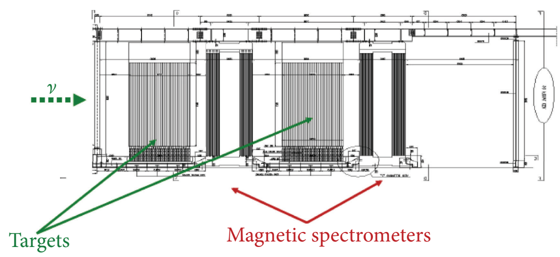


Figure 13: Schematic of the OPERA experiment in Hall C at Gran Sasso.

The muons are monitored by two silicon detectors. The mean ν_μ energy is 17 GeV. The muon beam size at the second muon detector at CERN is ~1 m; the ν_μ beam size at Gran Sasso is ~1 km. Figure 12 shows the 730 km path of the ν_μ beam from CERN to the Gran Sasso Lab (LNGS). It also indicates the synchronization via GPS of the atomic clocks at CERN and at LNGS. The CNGS beam was conceived to study the oscillation phenomenon in appearance mode; the E_ν spectrum was tuned to maximize the τ lepton production above its 3.5 GeV kinematic threshold.

During the 90s the ν_τ appearance was searched for in the "cosmologically relevant region" $\Delta m^2 > 1\,\text{eV}^2$ by two short-baseline experiments, *CHORUS* [110] and *NOMAD* [111], which relied on different techniques to search for τ appearance. Both experiments excluded $\nu_\mu \to \nu_\tau$ oscillations for $\Delta m^2 \gtrsim 1\,\text{eV}^2$.

OPERA at LNGS is a hybrid emulsion-electronic detector (Figure 13), designed to search the ν_τ appearance in the CNGS ν_μ beam [112–115], in the parameter region indicated by the atmospheric neutrino experiments. The ν_τ appearance search is based on the detection of the τ lepton in nuclear emulsions. The 1.25 kt target is segmented in units (*bricks*) consisting of 56 lead plates (1 mm thick) and 57 emulsion layers; each brick weighs 8.3 kg. Events may be analyzed in the electronic detector and/or in the emulsions. Fast automated scanning systems running at $\gtrsim$20 cm^2/h per emulsion layer were developed to cope with the emulsion analysis load [112–121]. In a brick the spatial and angular resolutions are <1 μm and ~2 mrad.

So far OPERA found three $\nu_\mu \to \nu_\tau$ candidate events (Figure 14) [122–124]. In Figure 14(a) tracks 1–6 originate from the primary interaction vertex, and track 7 is a prompt neutral particle, and track 4 has a kink topology compatible with a τ-lepton decay. γ_1 and γ_2 in Figure 14(b) are γ-rays from the secondary vertex; their invariant total mass is compatible with $\pi^0 \to 2\gamma$ decay. Track 8 is from a π^-. The invariant mass of the π^0 and of the π^- is compatible with that of $\rho(770)$ mass. The decay of the short track is thus compatible with $\tau^- \to \rho^-\nu_\tau$. The second and third event are shown in Figures 14(b) and 14(c). From these results the evidence for $\nu_\mu \to \nu_\tau$ appearance can be established at the 3.4σ level [123, 124]. The analysis of events is ongoing; the final result of ν_τ appearance search is expected by the end of 2014.

The OPERA search for $\nu_\mu \to \nu_e$ limited the window region for the LSND anomaly [125].

OPERA made a measurement of the ν_μ velocity and, after solving some technical problems, obtained precision measurements with the normal beam $(\nu_\mu - c)/c = 2.7 \pm 3.1(\text{stat.}) \pm 3.3(\text{syst.}) \times 10^{-6}$ and with a special "bunched beam" $-1.8 \times 10^{-6} < (\nu_\mu - c)/c < 2.3 \times 10^{-6}$ [125–128].

The *ICARUS T600* detector is an innovative TPC liquid argon detector which ran on the CNGS beam, in Hall B of LNGS. One event recorded by T600 is shown in Figure 15. ICARUS performed a search for ν_μ to ν_e limiting the window of open options for the LSND anomaly [129, 130].

The *T2K* (from Tokai to Kamioka) experiment is a second generation long baseline experiment, which uses a 2.5° off-axis neutrino beam produced by 30 GeV protons at the Japan Proton Accelerator Research Complex (J-PARC) [131]. The neutrino beam is sent to the SK detector, 295 km away; because of the kinematics of pion decay it emerges as a narrow beam peaked at 600 MeV. The schematic view of the neutrino beam line is sketched in Figure 16(a). A sophisticated near

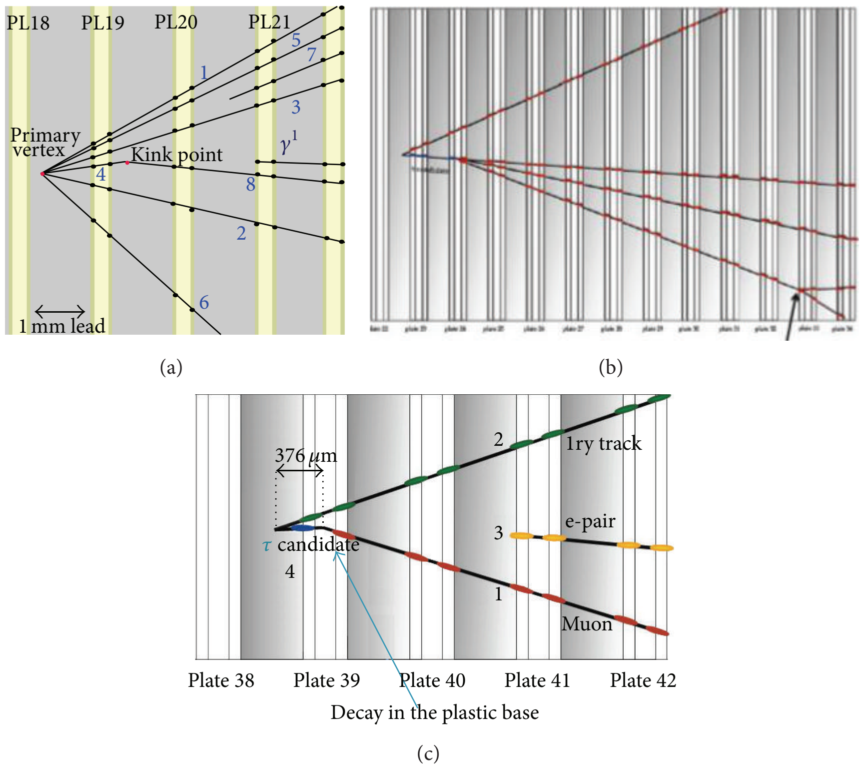


Figure 14: Display of three $\nu_\mu \rightarrow \nu_\tau$ candidate events from the OPERA experiment. (a) First event $\nu_\mu \rightarrow 4h + \nu_\tau$, $\tau \rightarrow e^- + \pi^\circ$, (b) second event $\nu_\mu \rightarrow h + \nu_\tau$, $\nu_\tau \rightarrow 3h$, and (c) third event $\nu_\mu \rightarrow h + \nu_\tau$, $\nu_\tau \rightarrow \mu$.

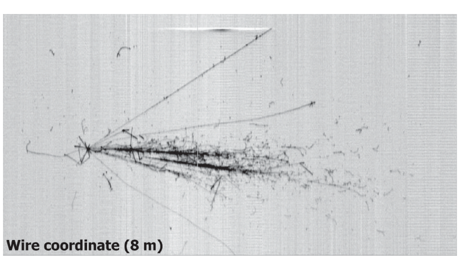


Figure 15: One CNGS event recorded in the ICARUS T600 detector.

detector complex (ND280) was built at a distance of 280 m from the target. It includes the on-axis monitor INGRID and an off-axis detector, a spectrometer with a magnetic field of 0.2 T which includes a π^0 detector, a projection chamber system, two scintillation detectors, a 4π electromagnetic calorimeter, and a muon range detector. A single μ-like beam event detected in the SK detector is shown in Figure 16(b). 28 $\nu_\mu \rightarrow \nu_e$ candidate events were detected and compared to an expected background of 4.6 ± 0.4 events. The excess events at SK correspond to a 90% confidence interval of $0.034 < \sin^2 2\theta_{13} < 0.190$ for normal hierarchy [132–135], and now it has a 7.5σ significance for $\nu_\mu \rightarrow \nu_e$ [96].

The *NOνA* experiment, which will run using an upgraded NuMI beam, is in an advanced construction phase. A proton beam power of ~0.7 MW is planned, with $E_\nu \sim 2$ GeV and a baseline of 810 km, 14 mrad off-axis. The detector will be a 15 kt "totally active" tracking liquid scintillator, scheduled to be partly operational by the end of 2013. It will be placed at ground level in Northern Minnesota. The close detector will be a 220 t replica of the far detector, placed 14 mrad off-axis at ~1 km from the target. The main NOνA physics aims include the study of ν_μ disappearance and ν_e appearance with a precision about one order of magnitude better than at present [136].

5.1. The LSND Δm^2 Scale. In the 90s at the Los Alamos Laboratory in New Mexico the 800 MeV proton linear accelerator was used to produce a ν_μ beam with energies up to 300 MeV (from muon decays at rest) incident on the Liquid Scintillator Neutrino Detector (LSND), designed primarily to search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations. A 3.8 sigma excess of $\overline{\nu}_e$ candidate events was observed and interpreted as due to neutrino oscillations with a small mixing angle and a relatively large Δm^2 in the 0.2–10 eV^2 range [137, 138]. The results do not fit in the conventional 3 neutrino mixing scheme and require at least a fourth neutrino (sterile neutrino).

The *KARMEN* [139] reactor experiment partly ruled out the LSND results leaving a small region, 0.2–2 eV^2, still compatible with the LSND oscillation signal.

The *MiniBooNE* experiment was designed to provide a test of the LSND signal. It used the Fermilab Booster neutrino beam generated from 8 GeV protons incident on a Be target. The center of MiniBooNE was 541 m from the production target. The near neutrino target was mineral oil in which relativistic particles created both Cherenkov and scintillation

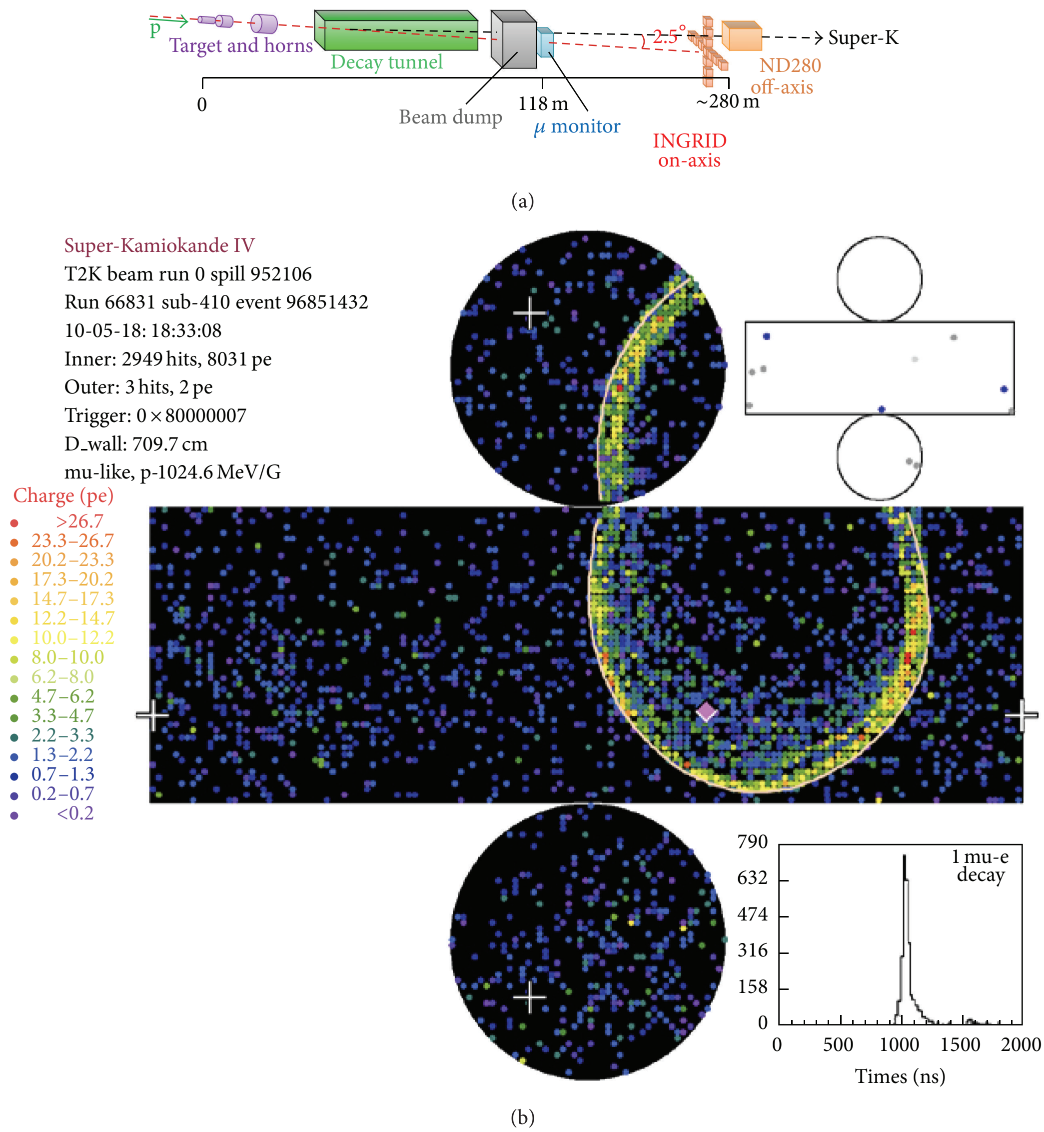


FIGURE 16: Sketch (a) of the T2K beam line, showing the primary proton beam line, the target station, the decay volume, the beam dump, the muon monitors, and the near on-axis and off-axis neutrino detectors. On (b) a single ring ν_μ event in the SK detector.

light. The experiment did not confirm the LSND results but found an excess of electron-like events in the neutrino energy range below 475 MeV [140]. The source of the excess remains unexplained, although several hypotheses were put forward [141, 142]. MiniBooNE reported on an updated search in antineutrino mode: an excess of $\overline{\nu}_e$ events for energies above 475 MeV was observed. The fit allowed regions for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations in the 0.1 to 1 eV^2 Δm^2 range are consistent with the allowed region reported by LSND.

The search for sterile neutrinos is very active. The SM already provides right-handed neutrinos, which are "sterile" with respect to gauge bosons of the electroweak sector. Experimental searches concern light sterile neutrinos ($m_\nu \sim$ 1 eV), which could mix with active neutrinos and oscillate at short baselines.

In addition to the LSND and MiniBooNE results, which involve electron (anti)neutrino appearance in ν_μ, $\overline{\nu}_\mu$ beams, other anomalies in disappearance mode were found to fit the same sterile neutrino scenario at the eV scale. The so-called "gallium anomaly" refers to the ν_e deficit in radioactive source calibration tests, at the gallium solar neutrino experiments SAGE and GALLEX [143]. A reevaluation of $\overline{\nu}_e$ flux from reactors exceeded the measured value by ~6% ("reactor anomaly") [144]. A recent reanalysis stresses that uncertainties may be larger than the anomaly [145]. When interpreted in terms of active to sterile neutrino oscillations, both gallium and reactor anomalies lead to oscillation parameters compatible with LSND and MiniBooNE results. It should be noted that the no-oscillation hypothesis is rejected at about 6σ, even if most of the statistical power is driven by LSND: removing LSND from the analysis, the oscillation significance drops to about 2σ [146]. Moreover it was found that the ν_μ disappearance channel is compatible with no oscillations in contradiction to what is expected, thus generating a tension with respect to previous results. The ν_μ disappearance channel in this Δm^2 region will be explored using atmospheric neutrinos in large acceptance detectors such as neutrino telescopes [147]. In the near future the SOX experiment will test the reactor and gallium anomalies by detecting neutrinos and antineutrinos from MCi sources, with Borexino [148].

Among the various ideas to tackle the sterile neutrino problem the SPSC-P-347 proposal (ICARUS-NESSiE) at CERN would be a complete experimental setup to solve this issue. The project would exploit the ICARUS T600 detector as a far detector in a new low energy ν_μ beam line at the CERN SPS. In addition a 150 t LAr detector clone could be placed at 460 m from the target position to provide the unoscillated pattern. Two magnetic spectrometers would be placed downstream of the two LAr-TPC detectors to complement and enlarge the physics reach of the experiment. The LAr-TPC technology allows identifying and reconstructing ν_e interactions. Muon neutrinos could be also identified even if charge reconstruction would be performed only at a statistical level with a large discrimination power. The spectrometers could complement and improve the muon neutrino sector by extending the measurable spectrum and performing charge identification at the 1% level on an event-by-event basis. The ICARUS-NESSiE proposal could span a large fraction of the parameter space in a limited time window simultaneously facing the ν_e appearance and ν_μ disappearance channels and also providing a measurement of NC rates which are considered reliable signals of sterile neutrino existence [149–152].

6. Neutrino Oscillations and New Physics

Mechanisms other than flavor transitions have been tested as alternative or subdominant processes to explain atmospheric ν_μ data (i.e., violation of the equivalence principle, of Lorentz invariance, and of CPT symmetry) [153]. The most relevant feature of these scenarios is the departure of the energy dependence of the oscillation length.

Lorentz Invariance Violation (LIV). MACRO and SK up-through-going muon data were used to search for subdominant oscillations due to a possible LIV: in this case there could be mixing between flavor and velocity eigenstates. Limits were placed in the Lorentz violation parameter $|\Delta v| < 6 \cdot 10^{-24}$ at $\sin 2\theta_v = 0$ and $|\Delta v| < 4 \times 10^{-26}$ at $\sin 2\theta_v = \pm 1$ [154]. In the context of a Standard Model Extension (SME) quantum strings could introduce nonlocality that could break Lorentz and/or CPT invariance. The neutrino oscillation probability may depend on the direction of the neutrino propagation; this effect would manifest, in experiments with both neutrino source and detector fixed on Earth, as a sidereal modulation in the number of detected neutrinos. This was searched for by the MINOS near detector without finding any effect: in the context of SME one could set limits on the magnitude of the Lorentz and CPT violating terms at the level of 10^{-4}–10^{-2} of the maximum expected, assuming a suppression of the signature by a factor of 10^{-17} [155]. More stringent limits may be obtained by neutrino telescopes; see Section 8.

Neutrino Decay. Using SK data Fogli et al. [79, 80] have shown that the neutrino decay hypothesis fails to reproduce the observed zenith angle distribution of atmospheric neutrinos. MINOS excluded neutrino decay at 7 standard deviations studying the L/E_ν distribution [104].

The radiative decay modes allowed for massive neutrinos are $\nu_2 \rightarrow \nu_1 + \gamma$ and $\nu_3 \rightarrow \nu_{2,1} + \gamma$ [62]. A direct experimental limit comes from the 2006 total solar eclipse in the Libya Sahara desert [63]. For the $\nu_2 \rightarrow \nu_1 + \gamma$ radiative decay the 95% CL lower lifetime limits are in the range $10\,\mathrm{s} \div 10^9\,\mathrm{s}$ for neutrino masses $10^{-4}\,\mathrm{eV} < m_1 < 0.1\,\mathrm{eV}$ [63]. A similar limit was obtained for the $\nu_3 \rightarrow \nu_{2,1} + \gamma$ decay, but the limit is tentative since it depends on the mixing angle θ_{13} which was not known at that time.

Extra Dimensions. In models where the standard $1 + 3$ dimensional world ("brane") is embedded in a larger $1 + 3 + d$ dimensional spacetime ("bulk")—with d being the number of extra dimensions—and SM left-handed neutrinos are frozen within the brane while right-handed neutrino singlets can propagate in the bulk. They give rise to perturbations that can alter the "standard" oscillation pattern of active neutrinos. By combining the results from KamLAND and MINOS a limit $\lesssim 1\,\mu$m was obtained on the size of the larger hidden dimension [156].

Lepton Flavor Violation. Neutrino oscillations arise from flavor mixing in the leptonic sector. In the SM the violation would be minimal and lead to a very small branching ratios for processes which violate lepton flavor, like $\mu \rightarrow e\gamma$ decay. Supersymmetric (SUSY) theories could give rise to lepton flavor violations through radiative corrections which could increase the branching ratio. This could happen also for electric dipole moments, for example, of the neutron and of the muon. The MEG collaboration published limits on the search for $\mu^+ \rightarrow e^+\gamma$ decay: $< 5.7 \times 10^{-13}$ (90% CL) [157].

7. Cross Section and Particle Production Measurements

After 1998 it was realized that the existing measurements of hadron production concerned mainly very forward angles and high momenta and were not adequate for the proper atmospheric neutrino simulations and for conventional and advanced neutrino beams. In 2000 the *HARP* experiment at the CERN-SPS pioneered systematic hadron production measurements over the full acceptance in angle and in momentum. It used proton and pion beams on different target materials [158]. It produced the pion data needed for the K2K and MiniBooNE experiments.

New neutrino cross-section measurements were also made by the K2K near detector (~1.2 GeV), MiniBooNE (~800 MeV), SciBooNE (~800 MeV) [159, 160], MIPP (from 1 to 120 GeV), NA61/SHINE experiment at the CERN-SPS [161, 162], and T2K [163].

The *MINERvA* experiment in the NuMI beam-line at Fermilab is a fine-grained detector which will provide neutrino scattering data in the ~1–20 GeV region [164–167].

8. Neutrino Telescopes and Atmospheric Neutrinos

Large size neutrino telescopes were built mainly to shed light on the most violent and energetic phenomena in the universe using high energy neutrinos as astrophysical probes. High energy neutrinos with hundreds of GeV may come from nonthermal astrophysical sources [168]. Multi-GeV neutrinos may also come from the interior of celestial bodies, like the sun, some planets, and the center of our galaxy where annihilation of weakly interactive massive particles (WIMPs) could take place. These searches require large detectors, like the Baikal detector in lake water [169], Amanda [170] and IceCube [171–173] in South Pole ice, and ANTARES in the Mediterranean sea [174–176]; a multi-km^3 detector is planned for the Mediterranean sea (Km3NeT) [177]. The observation of neutrinos is based on the Cherenkov light induced by upgoing muons produced in high energy CC ν_μ interactions (to reduce the background from atmospheric muons, neutrino telescopes look downward). Large arrays of PMTs cover huge volumes of ice or sea water.

The cosmic very high energy neutrino flux is expected to decrease with energy as E^{-2}. Atmospheric neutrinos are a background with an energy dependence of $E^{-3.7}$. The possibility to perform neutrino oscillation studies is related to the energy threshold for detecting lower energy atmospheric neutrinos. If the spacing between neutrino telescope strings is reduced (as in the IceCube Deep Core array), the energy threshold is ~20 GeV. It could be as low as few GeV in the future Km3NeT-ORCA and IceCube-PINGU inner cores. This opens the possibility to perform high statistics oscillation analyses up to ~1 TeV, above which the Earth starts to become opaque to neutrinos. The IceCube present Inner Core allowed a first measurement of the atmospheric ν_μ oscillations which yielded in a 2-ν flavor formalism: $\Delta m^2_{23} = (2.3^{+0.6}_{-0.5}) \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) > 0.73$. The no-oscillation hypothesis is rejected [178–181]. The ANTARES experiment obtained a measurement of $|\Delta m^2_{23}|$ of limited accuracy, $|\Delta m^2_{23}| = (3.1 \pm 0.9) \times 10^{-3}$ eV^2, but it checks the status of the apparatus and underlines the potential for future physics [174–176].

Figure 17 shows the atmospheric ν_μ energy spectrum in the range 0.1–400 TeV, measured by the IceCube, ANTARES, and AMANDA-II neutrino telescopes, using different energy estimators and different unfolding methods. The data are compared with the MC Bartol flux and with the more elaborate Bartol + Martin, Bartol + Enberg calculations. Within large systematic errors, the results from different experiments are compatible with each other and with the theoretical MC predictions [182–184]. The data do not confirm nor reject the presence of prompt components.

Neutrino telescopes have searched for Lorentz invariance violations. IceCube, operating in a 40-string configuration, searched for a periodic variation in right ascension, a possible consequence of LIV preferred frame. No such direction-dependent variation was found, and, due to the unique high energy reach of IceCube, it was possible to improve constraints on certain LIV oscillation by about three orders of magnitude with respect to other experiments [178–181].

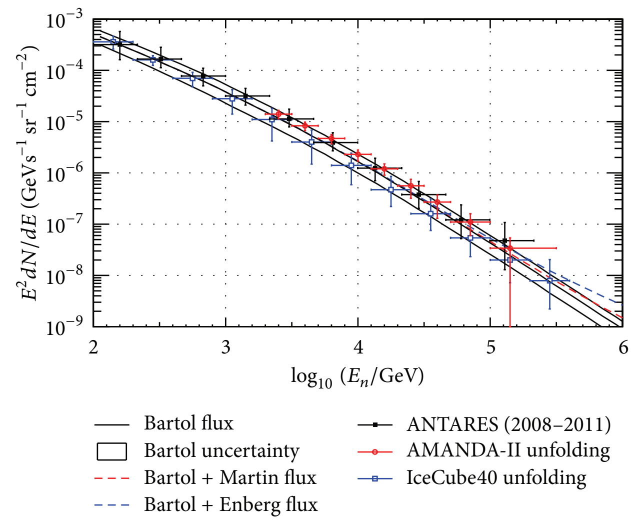


Figure 17: Atmospheric muon neutrino spectrum in the 0.1–200 TeV energy range, measured by ANTARES, AMANDA-II, and IceCube compared with the Bartol, Bartol + Martin, and Bartol + Enberg MC fluxes.

Very large neutrino telescopes could also yield more precise direct and indirect results on dark matter (*WIMPs*) and on the searches for various exotic particles.

9. Conclusions and Perspectives

The standard model of particle physics obtained important confirmations in all experiments at LEP, SLC (e^+e^-), HERA (e^+p), and Fermilab ($\bar{p}p$) colliders, and a Higgs boson-like particle has been seen at the CERN LHC, but the SM needs further confirmations.

Neutrino oscillations provided a first indication for physics beyond the standard model. The atmospheric neutrino anomaly was experimentally observed and explained as due to neutrino oscillations with maximal mixing and $|\Delta m^2_{23}| \simeq 2.4 \times 10^{-3}$ eV^2. It was later confirmed with more data and by the long baseline neutrino experiments, including appearance experiments ($\nu_\mu \leftrightarrow \nu_\tau$) with ν_τ direct detection in nuclear emulsions.

It may be interesting to consider the variations with time of the atmospheric oscillation parameters published by different experiments. In the two neutrino scenario, $\nu_\mu \to \nu_\tau$, most experiments obtained maximal mixing and values of $|\Delta m^2_{23}|$ which changed only slightly with time (in units of 10^{-3} eV^2):

(i) in 1998: 2.3 (SK), 2.5 (MACRO), and 5.2 (Soudan-2),

(ii) in 2004: 2.5 (SK), 2.3 (MACRO),

(iii) in 2006: 2.8 (K2K),

(iv) in 2008: 2.43 ± 0.12 (MINOS),

(v) in 2010: $2.32^{+0.11}_{-0.08}$ (MINOS), 2.2-2.3 (SK 2-flavor; 2.11 and 2.51 SK 3-flavor analyses for normal and inverted hierarchy, resp. [81]),

(vi) in 2013: 2.41 ± 0.10 (MINOS), $\sin^2 2\theta_{23} = 0.950 \pm 0.036$, 2.44 (T2K), $\sin^2 2\theta_{23} \simeq 1$, 2.3 ± 0.5 (IceCube DeepCore), and $\sin^2(2\theta_{23}) > 0$, 3.1 ± 0.9 (ANTARES).

Globally the variations and the differences among the values from different experiments are small and well within their systematic errors. The variations are negligible compared to those reported in the early experiments on weak interactions and early atmospheric ν experiments.

In the three-active-neutrino frameworks one would like to solve the so-called "eightfold" degeneracy. Assuming the measured value of θ_{13} and running in $\nu/\overline{\nu}$ mode there are two different sets of parameters $(\theta_{13}, \delta_{CP})$ producing the same oscillation probabilities. These "clone solutions" are doubled by the unknown sign of Δm^2_{23} (normal or inverted hierarchy) and redoubled by the θ_{23} octant degeneracy, that is, the sign of $(\theta_{23} - \pi/4)$. The problem may be solved by performing complete 3 neutrino analyses and by considering combinations of different baselines and energies [185, 186].

Several groups worldwide are investigating future neutrino beams of higher intensity and purity: *superbeams*, *beta-beams,* and *neutrino factories* [187, 188]. High intensity ν_μ beams (*superbeams*) from high intensity proton accelerators are based on the improvements of existing proton accelerator complexes. *Beta-beams* could be produced from radioactive ion beams, taking advantage of the technological progress in this field. The beta decays of unstable ions would lead to pure sources of ν_e and $\overline{\nu}_e$ beams, which could be used to study $\nu_e \rightarrow \nu_\mu$ oscillations. High energy muon colliders have been studied for several purposes, in particular to obtain electron and muon neutrino beams from muon decays. The goal is to make high energy and high intensity muon storage rings which could be used as *neutrino factories*. It was proposed that simultaneous μ^- and μ^+ decays could lead to important tests of CP violation in the leptonic sector [186, 188, 189].

The recent measurements of $\theta_{13} \simeq 9^\circ$, together with the plans for upgraded higher intensity neutrino beams and new large refined detectors, open the door to a new golden age for neutrino physics, where one could obtain important information on neutrino masses and neutrino hierarchy, establish if θ_{23} is maximal or, if it is not, in which octant it lies, and make important tests of CP violation in the leptonic sector.

New large neutrino telescopes may improve the knowledge on dark matter, on supernovae neutrinos, and on the measurements of some parameters of atmospheric neutrino oscillations. Do sterile neutrinos exist? Are sterile neutrinos the explanation of existing experimental data which cannot be reconciled with the standard mixing scenario?

The search for new physics beyond the SM will be one of the main fields of research at the LHC. Supersymmetry is still one of the theoretically favored models and this could shed light on dark matter. Other topics such as compositeness, technicolor, and extra dimensions could be searched for at the new energy frontier. LHC may also yield information on neutrinos [190].

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References

[1] B. Pontecorvo, "Mesonium and anti-mesonium," *Soviet Physics. JETP*, vol. 6, p. 429, 1957.

[2] B. Pontecorvo, "Inverse beta processes and non conservation of lepton charge," *Soviet Physics. JETP*, vol. 7, p. 172, 1958.

[3] Z. Maki, M. Nakagawa, and S. Sakata, "Remarks on the unified model of elementary particles," *Progress of Theoretical Physics*, vol. 28, no. 5, pp. 870–880, 1962.

[4] B. Pontecorvo, "Neutrino experiments and the problem of conservation of leptonic charge," *Soviet Physics. JETP*, vol. 26, p. 984, 1968.

[5] R. Davis Jr., D. S. Harmer, and K. C. Hoffman, "Search for neutrinos from the sun," *Physical Review Letters*, vol. 20, no. 21, pp. 1205–1209, 1968.

[6] B. T. Cleveland, T. Daily, R. Davis Jr. et al., "Measurement of the solar electron neutrino flux with the homestake chlorine detector," *Astrophysical Journal Letters*, vol. 496, no. 1, pp. 505–526, 1998.

[7] J. N. Bahcall, "Solar neutrinos. I. theoretical," *Physical Review Letters*, vol. 12, no. 11, pp. 300–302, 1964.

[8] J. N. Bahcall and R. Davis, "On the problem of detecting solar neutrinos," BNL-8217, 1964.

[9] J. N. Bahcall, P. I. Krastev, and A. Y. Smirnov, "Where do we stand with solar neutrino oscillations?" *Physical Review D*, vol. 58, no. 9, Article ID 096016, 1998.

[10] J. N. Bahcall, W. A. Fowler, I. Iben, and R. L. Sears, "Solar neutrino flux," *The Astrophysical Journal*, vol. 137, p. 344, 1963.

[11] P. Anselmann, W. Hampel, G. Heusser et al., "GALLEX results from the first 30 solar neutrino runs," *Physics Letters B*, vol. 327, no. 3-4, pp. 377–385, 1994.

[12] J. N. Abdurashitov, V. N. Gavrin, S. V. Girin et al., "Measurement of the solar neutrino capture rate with gallium metal," *Physical Review C*, vol. 60, no. 5, Article ID 055801, 32 pages, 1999.

[13] J. N. Abdurashitov, E. L. Faizova, V. N. Gavrin et al., "Results from SAGE-The Russian-American gallium solar neutrino experiment," *Physics Letters B*, vol. 328, no. 1-2, pp. 234–248, 1994.

[14] M. Altmann, M. Balata, P. Belli et al., "Complete results for five years of GNO solar neutrino observations," *Physics Letters B*, vol. 616, no. 3-4, pp. 174–190, 2005.

[15] K. S. Hirata, T. Kajita, T. Kifune et al., "Observation of ^{8}B solar neutrinos in the Kamiokande-II detector," *Physical Review Letters*, vol. 63, no. 1, 16 pages, 1989.

[16] K. S. Hirata, K. Inoue, T. Kajita et al., "Results from one thousand days of real-time, directional solar-neutrino data," *Physical Review Letters*, vol. 65, no. 11, pp. 1297–1300, 1990.

[17] Q. R. Ahmad et al., "Measurement of the rate of $\nu_e + d \rightarrow p + p + e^-$ interactions produced by ^8B solar neutrinos at the

Sudbury Neutrino Observatory," *Physical Review Letters*, vol. 87, no. 7, Article ID 071301, 6 pages, 2001.

[18] Q. R. Ahmad, R. C. Allen, T. C. Andersen et al., "Direct evidence for neutrino flavor transformation from neutral-current interactions in the Sudbury Neutrino Observatory," *Physical Review Letters*, vol. 89, no. 1, Article ID 011301, 6 pages, 2002.

[19] K. Eguchi, S. Enomoto, K. Furuno et al., "First results from KamLAND: evidence for reactor antineutrino disappearance," *Physical Review Letters*, vol. 90, no. 2, Article ID 021802, 6 pages, 2003.

[20] C. Arpesella, G. Bellini, J. Benziger et al., "First real time detection of ^{7}Be solar neutrinos by Borexino," *Physics Letters B*, vol. 658, no. 4, pp. 101–108, 2008.

[21] C. Arpesella, H. O. Back, M. Balata et al., "Direct measurement of the ^{7}Be solar neutrino flux with 192 days of Borexino data," *Physical Review Letters*, vol. 101, Article ID 091302, 6 pages, 2008.

[22] R. Becker-Szendy, C. B. Bratton, D. Casper et al., "Electron- and muon-neutrino content of the atmospheric flux," *Physical Review D*, vol. 46, no. 9, pp. 3720–3724, 1992.

[23] D. Casper, R. Becker-Szendy, C. B. Bratton et al., "Measurement of atmospheric neutrino composition with the IMB-3 detector," *Physical Review Letters*, vol. 66, no. 20, pp. 2561–2564, 1991.

[24] K. S. Hirata, K. Inoue, T. Ishida et al., "Observation of a small atmospheric ν_μ/ν_e ratio in Kamiokande," *Physics Letters B*, vol. 280, no. 1-2, pp. 146–152, 1992.

[25] K. S. Hirata, T. Kajita, M. Koshiba et al., "Experimental study of the atmospheric neutrino flux," *Physics Letters B*, vol. 205, no. 2-3, pp. 416–420, 1988.

[26] Y. Fukuda, T. Hayakawa, K. Inoue et al., "Atmospheric ν_μ/ν_e ratio in the multi-GeV energy range," *Physics Letters B*, vol. 335, pp. 237–245, 1994.

[27] M. Aglietta, G. Battistoni, E. Bellotti et al., "Experimental study of atmospheric neutrino flux in the NUSEX experiment," *Europhysics Letters*, vol. 8, no. 7, article 611–614, 1989.

[28] Ch. Berger, M. Fröhlich, H. Mönch et al., "Study of atmospheric neutrino interactions with the Fréjus detector," *Physics Letters B*, vol. 227, no. 3-4, pp. 489–494, 1989.

[29] K. Daum, W. Rhode, P. Bareyre et al., "Determination of the atmospheric neutrino spectra with the Fréjus detector," *Zeitschrift für Physik C*, vol. 66, no. 3, pp. 417–428, 1995.

[30] M. Boliev, A. V. Butkevich, V. N. Zakidyshev et al., "Limitations on parameters of neutrino oscillations according to data of the baksan underground telescope," *Yadernaya Fizika*, vol. 34, pp. 1418–1421, 1981, Soviet Journal of Nuclear Physics, vol. 34, pp. 787, 1981.

[31] M. M. Boliev, A. V. Butkevich, A. E. Chudakov et al., "Observation of upward through-going muons with the Baksan detector: an update," *Nuclear Physics B*, vol. 70, no. 1–3, pp. 371–373, 1999.

[32] W. W. M. Allison, G. J. Alner, D. S. Ayres et al., "Measurement of the atmospheric neutrino flavour composition in Soudan 2," *Physics Letters B*, vol. 391, pp. 491–500, 1997.

[33] E. Peterson, "Atmospheric neutrino studies in Soudan 2," *Nuclear Physics B*, vol. 77, no. 1–3, pp. 111–116, 1999.

[34] M. Ambrosio, R. Antolini, C. Aramo et al., "Measurement of the atmospheric neutrino-induced upgoing muon flux using MACRO," *Physics Letters B*, vol. 434, no. 3-4, pp. 451–457, 1998.

[35] F. Ronga, "Atmospheric neutrino induced muons in the MACRO detector," *Nuclear Physics B*, vol. 77, no. 1–3, pp. 117–122, 1999.

[36] P. Bernardini, "Measurement of the Atmospheric Neutrino Induced Muon Flux with the MACRO detector," in *Proceedings of the Vulcano Workshop*, Vulcano, Italy, May 1998.

[37] S. P. Ahlen, M. Ambrosio, R. Antolini et al., "Atmospheric neutrino flux measurement using upgoing muons," *Physics Letters B*, vol. 357, no. 3, pp. 481–486, 1995.

[38] Y. Fukuda, T. Hayakawa, E. Ichihara et al., "Evidence for oscillation of atmospheric neutrinos," *Physical Review Letters*, vol. 81, no. 8, pp. 1562–1567, 1998.

[39] V. Agrawal, T. K. Gaisser, P. Lipari, and T. Stanev, "Atmospheric neutrino flux above 1 GeV," *Physical Review D*, vol. 53, no. 3, pp. 1314–1323, 1996.

[40] M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, "Calculation of the flux of atmospheric neutrinos," *Physical Review D*, vol. 52, no. 9, pp. 4985–5005, 1995.

[41] M. Honda, T. Kajita, K. Kasahara et al., "Comparison of 3-dimensional and 1-dimensional schemes in the calculation of atmospheric neutrinos," *Physical Review D*, vol. 64, Article ID 053011, 12 pages, 2001.

[42] T. Kajita, K. Kasahara, and S. Midorikawa, "New calculation of the atmospheric neutrino flux in a three dimensional scheme," *Physical Review D*, vol. 70, no. 4, Article ID 043008, 17 pages, 2004.

[43] G. Battistoni, A. Ferrari, T. Montaruli, and P.R. Sala, "The FLUKA atmospheric neutrino flux calculation," *Astroparticle Physics*, vol. 19, no. 2, pp. 269–290, 2003.

[44] G. Altarelli, "Status of the standard model at the LHC start," *Nuovo Cimento della Societa Italiana di Fisica B*, vol. 123, no. 3-4, pp. 257–269, 2008.

[45] G. Giacomelli, "The standard model of particle physics. Neutrino oscillations," *Radiation Measurements*, vol. 44, no. 9-10, pp. 826–833, 2009.

[46] The ALEPH, DELPHI, L3, OPAL, SLD Collab, and The LEP EW Working Group and The SLD EW and Heavy Flavour Groups, "Precision EW measurements on the Z resonance," *Physics Reports*, vol. 427, no. 5-6, pp. 257–454, 2006.

[47] S. Schael, R. Barate, R. Brunelière et al., "Search for neutral MSSM Higgs bosons at LEP," *The European Physical Journal C*, vol. 47, no. 3, pp. 547–587, 2006.

[48] G. Giacomelli and R. Giacomelli, "The LEP legacy," http://arxiv.org/abs/hep-ex/0503050.

[49] J. Beringer, J.-F. Arguin, R. M. Barnet et al., "Review of particle physics," *Physical Review D*, vol. 86, no. 1, Article ID 010001, 1528 pages, 2012.

[50] A. R. Ade, N. Aghanim, and C. Armitage-Caplan, "Planck 2013 results. XVI. Cosmological parameters," http://arxiv.org/abs/1303.5076.

[51] G. Aad, T. Abajyan, B. Abbott et al., "Observation of a new particle in the search for the SM Higgs boson with the ATLAS detector at the LHC," *Physics Letters B*, vol. 716, no. 1, pp. 1–29, 2012.

[52] S. Chatrchyan, V. Khachatryan, A.M. Sirunyan et al., "Observation of a new boson with mass near 125 GeV in pp collisions at sqrt(s) = 7 and 8 TeV," *Physics Letters B*, vol. 716, no. 1, pp. 30–61, 2012.

[53] C. Biggio, L. Calibbi, A. Masiero, and S. K. Vempati, "Postcards from oases in the desert: phenomenology of SUSY with intermediate scales," *Journal of High Energy Physics*, vol. 1208, article 150, 2012.

[54] T. Schwetz, M. Tórtola, and J. W. F. Valle, "Three-flavour neutrino oscillation update," *New Journal of Physics*, vol. 10, Article ID 113011, 2008.

[55] L. Wolfenstein, "Neutrino oscillations in matter," *Physical Review D*, vol. 17, no. 9, pp. 2369–2374, 1978.

[56] S. P. Mikheyev and A. Yu. Smirnov, "Resonance amplification of oscillations in matter and spectroscopy of solar neutrinos," *Soviet Journal of Nuclear Physics*, vol. 42, pp. 913–917, 1985, Il Nuovo Cimento C, vol. 9, pp. 17, 1986.

[57] G. Giacomelli and M. Sioli, "Astroparticle physics," in *Lectures at the 6th Constantine School on Weak and Strong Interaction Phenomenology*, Constantine, Algeria, 2002.

[58] G. Giacomelli and P. Giacomelli, "Particle searches at LEP," *La Rivista del Nuovo Cimento*, vol. 16, no. 3, pp. 1–59, 1993.

[59] R. Barate et al., "An upper limit on the τ neutrino mass from three- and five-prong tau decays," *The European Physical Journal C*, vol. 2, no. 3, pp. 395–406, 1998.

[60] C. Arnaboldi, D. R. Artusa, F. T. Avignone et al., "Results from a search for the $\nu\beta\beta$-decay of ^{130}Te)," *Physical Review C*, vol. 78, no. 3, Article ID 035502, 5 pages, 2008.

[61] E. Komatsu, K. M. Smith, J. Dunkley et al., "Seven-year wilkinson microwave anisotropy probe (WMAP) observations: cosmological interpretation," *Astrophysical Journal*, vol. 192, no. 2, 2011.

[62] D. W. Sciama, "The present status of the decaying neutrino theory," *Nuclear Physics B*, vol. 38, no. 1–3, pp. 320–323, 1995.

[63] S. Cecchini, D. Centomo, G. Giacomelli et al., "New lower limits on the lifetime of heavy neutrino radiative decay," *Astroparticle Physics*, vol. 34, no. 6, pp. 486–492, 2011.

[64] F. Reines, M. F. Crouch, T. L. Jenkins et al., "Evidence for high-energy cosmic-ray neutrino interactions," *Physical Review Letters*, vol. 15, no. 9, pp. 429–433, 1965.

[65] C. V. Achar, M. G. K. Menon, V. S. Narasimham et al., "Detection of muons produced by cosmic ray neutrinos deep underground," *Physics Letters*, vol. 18, no. 2, pp. 196–199, 1965.

[66] Y. Ashie, J. Hosaka, K. Ishihara et al., "Evidence for an oscillatory signature in atmospheric neutrino oscillations," *Physical Review Letters*, vol. 93, no. 10, Article ID 101801, 2004.

[67] Y. Ashie, J. Hosaka, K. Ishihara et al., "Measurement of atmospheric neutrino oscillation parameters by Super-Kamiokande I," *Physical Review D*, vol. 71, no. 11, Article ID 112005, 35 pages, 2005.

[68] M. Ambrosio, R. Antolini, D. Bakari et al., "Measurements of atmospheric muon neutrino oscillations, global analysis of the data collected with MACRO detector," *The European Physical Journal C*, vol. 36, no. 3, pp. 323–339, 2004.

[69] W. W. M. Allison, G. J. Alner, D. S. Ayres et al., "The atmospheric neutrino flavor ratio from a 3.9 fiducial kiloton-year exposure of Soudan 2," *Physics Letters B*, vol. 449, no. 1-2, pp. 137–144, 1999.

[70] M. Sanchez, W. W. M. Allison, G. J. Alner et al., "Measurement of the *L/E* distributions of atmospheric ν in Soudan 2 and their interpretation as neutrino oscillations," *Physical Review D*, vol. 68, no. 11, Article ID 113004, 14 pages, 2003.

[71] M. Ambrosio, R. Antolini, R. Assiro et al., "The MACRO detector at Gran Sasso," *Nuclear Instruments and Methods in Physics Research A*, vol. 486, no. 3, pp. 663–707, 2002.

[72] M. Ambrosio, R. Antolini, D. Bakari et al., "Atmospheric neutrino oscillations from upward throughgoing muon multiple scattering in MACRO," *Physics Letters B*, vol. 566, no. 1-2, pp. 35–44, 2003.

[73] M. Ambrosio, R. Antolini, G. Auriemma et al., "Low energy atmospheric muon neutrinos in MACRO," *Physics Letters B*, vol. 478, no. 1–3, pp. 5–13, 2000.

[74] M. Ambrosio, R. Antolini, G. Auriemma et al., "Matter effects in upward-going muons and sterile neutrino oscillations," *Physics Letters B*, vol. 517, no. 1-2, pp. 59–66, 2001.

[75] Y. Fukuda, S. Fukuda, M. Ishitsuka et al., "Tau neutrinos favored over sterile neutrinos in atmospheric muon neutrino oscillations," *Physical Review Letters*, vol. 85, no. 19, pp. 3999–4003, 2000.

[76] G. Giacomelli and M. Giorgini, "Atmospheric neutrino oscillations," in *Lecture at the 7th School on Non-Accelerator Astroparticle Physics*, Trieste, Italy, 2004.

[77] Y. Fukuda, T. Hayakawa, E. Ichihara et al., "Measurement of the flux and zenith angle distribution of upward through-going muons by Super Kamiokande," *Physical Review Letters*, vol. 82, no. 13, pp. 2644–2648, 1999.

[78] R. Wendell, C. Ishihara, K. Abe et al., "Atmospheric neutrino oscillation analysis with subleading effects in Super-Kamiokande I, II and III," *Physical Review D*, vol. 81, Article ID 092004, 16 pages, 2010.

[79] G. L. Fogli, E. Lisi, A. Marrone, and G. Scioscia, "Testing violations of special and general relativity through the energy dependence of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the Super-Kamiokande atmospheric neutrino experiment," *Physical Review D*, vol. 60, no. 5, pp. 1–9, 1999.

[80] G. L. Fogli, E. Lisi, A. Marrone, and G. Scioscia, "Super-Kamiokande data and atmospheric neutrino decay," *Physical Review D*, vol. 59, no. 11, Article ID 117303, 3 pages, 1999.

[81] Y. Suzuki, "Super-Kamiokande," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[82] K. Abe, Y. Hayato, T. Iida et al., "A measurement of the appearance of atmospheric tau neutrinos by SuperK," *Physical Review Letters*, vol. 110, no. 18, Article ID 181802, 7 pages, 2013.

[83] T. Kajita, "Discovery of neutrino oscillations," *Reports on Progress in Physics*, vol. 69, no. 6, pp. 1607–1635, 2006.

[84] G. Giacomelli, "Atmospheric ν's and long baseline neutrino experiments," in *AIP Conference Proceedings*, vol. 972, pp. 412–420, Sinaia, Romania, 2008.

[85] G. C. Trinchero, M. Ambrosio, M. Amelchakov et al., "MONOLITH: a massive magnetized iron detector for atmospheric neutrinos," in *Proceedings of the 27th International Cosmic Ray Conference*, Hamburg, Germany, August 2001.

[86] N. K. Mondal, "India-based Neutrino Observatory," *Pramana*, vol. 79, p. 1003, 2012.

[87] M. Apollonio, A. Baldini, C. Bemporad et al., "Search for neutrino oscillations on a long base-line at the chooz nuclear power station," *European Physical Journal C*, vol. 27, no. 3, pp. 331–374, 2003.

[88] F. Boehm, J. Busenitz, B. Cook et al., "Final results from the Palo Verde neutrino oscillation experiment," *Physical Review D*, vol. 64, no. 11, Article ID 112001, 2001.

[89] F. P. An, J. Z. Bai1, A. B. Balantekin et al., "Observation of electron-antineutrino disappearance at Daya Bay," *Physical Review Letters*, vol. 108, no. 17, Article ID 171803, 7 pages, 2012.

[90] F. P. An, Q. An, J. Z. Bai et al., "Improved measurement of electron antineutrino disappearance at Daya Bay," *Chinese Physics C*, vol. 37, no. 1, Article ID 011001, 2013.

[91] J. Cao, "Daya Bay: results and future," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[92] Y. Abe, "First measurement of θ_{13} from delayed neutron capture on hydrogen in the Double Chooz experiment," *Physics Letters B*, vol. 723, no. 1–3, pp. 66–70, 2013.

[93] A. Cabrera, "Double chooz," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[94] S.-H. Seo, "New results from RENO," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[95] J. K. Ahn, S. Chebotaryov, J. H. Choi et al., "Observation of reactor electron antineutrino disappearance in the RENO experiment," *Physical Review Letters*, vol. 108, no. 19, Article ID 191802, 6 pages, 2012.

[96] T2K exp, "T2K Observes $\nu_\mu > \nu_e$ definitively," *CERN Courier*, vol. 2013, 8 pages.

[97] S. Pascoli, "A theoretical perspective on neutrinos," in *Proceedings of the 26th International Lepton Photon Symposium*, San Francisco, Calif, USA, 2013.

[98] S. Dusini, A. Longhin, M. Mezzetto et al., "CP violation and mass hierarchy at medium baselines in the large teta13 era," *Europhysics Journal*, vol. C73, p. 2392, 2013.

[99] M. Gribier, "Reactor antineutrino anomalies and searches for sterile neutrinos in Europe," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[100] P. K. Huber, "Reactor neutrinos-fluxes and US Plans," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[101] J. Kopp, "Global status of sterile neutrino scenario," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, 2013.

[102] M. H. Ahn, E. Aliu, S. Andringa et al., "Measurement of neutrino oscillation by the K2K experiment," *Physical Review D*, vol. 74, no. 7, Article ID 072003, 39 pages, 2006.

[103] E. Aliu, S. Andringa, S. Aoki et al., "Evidence for muon neutrino oscillations in an accelerator-based experiment," *Physical Review Letters*, vol. 94, no. 8, Article ID 081802, 5 pages, 2005.

[104] P. Adamson, I. Anghel, C. Backhouse et al., "Measurement of neutrino and antineutrino oscillations using beam and atmospheric data in MINOS," *Physical Review Letters*, vol. 110, no. 25, Article ID 251801, 6 pages, 2013.

[105] K. Lang, "MINOS selected topics," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[106] V. Barger, J. G. Learned, P. Lipari, M. Lusignoli, S. Pakvasa, and T. J. Weiler, "Neutrino decay and atmospheric neutrinos," *Physics Letters B*, vol. 462, no. 1-2, pp. 109–114, 1999.

[107] E. Lisi, A. Marrone, and D. Montanino, "Probing possible decoherence effects in atmospheric neutrino oscillations," *Physical Review Letters*, vol. 85, no. 6, pp. 1166–1169, 2000.

[108] P. Adamson, C. Andreopoulos, K. E. Arms et al., "Meaurement of neutrino oscillations with the MINOS detectors in the NuMi beam," *Physical Review Letters*, vol. 101, no. 13, Article ID 131802, 2008.

[109] P. Adamson, C. Andreopoulos, K. E. Arms et al., "Study of muon neutrino disappearance using the Fermilab Main Injector neutrino beam," *Physical Review D*, vol. 77, no. 1, Article ID 072002, 2008.

[110] E. Eskut, A. Kayis-Topaksu, G. Önengüt et al., "Final results on $\nu_\mu \rightarrow \nu_\tau$ oscillations from the CHORUS experiment," *Nuclear Physics B*, vol. 793, no. 1-2, pp. 326–343, 2008.

[111] P. Astier, D. Autiero, A. Baldisseri et al., "Final NOMAD results on $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\tau$ oscillations including a new search for ν_τ appearance using hadronic tau decays," *Nuclear Physics B*, vol. 611, no. 1–3, pp. 3–39, 2001.

[112] R. Acquafredda, T. Adam, N. Agafonova et al., "The OPERA experiment in the CERN to Gran Sasso neutrino beam," *Journal of Instrumentation*, vol. 4, Article ID P04018, 2009.

[113] R. Acquafredda, N. Agafonova, M. Ambrosio et al., "First events from the CNGS neutrino beam detected in the OPERA experiment," *New Journal of Physics*, vol. 8, article 303, 2006.

[114] N. Agafonova, A. Anokhina, S. Aoki et al., "The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment," *Journal of Instrumentation*, vol. 4, Article ID P06020, 2009.

[115] A. Anokhina, S. Aoki, A. Ariga et al., "Emulsion sheet doublets as interface trackers for the OPERA experiment," *Journal of Instrumentation*, vol. 3, Article ID P07005, 2008.

[116] L. Arrabito, E. Barbuto, C. Bozza et al., "Hardware performance of a scanning system for high speed analysis of nuclear emulsions," *Nuclear Instruments and Methods in Physics Research A*, vol. 568, no. 2, pp. 578–587, 2006.

[117] L. Arrabito, D. Autiero, C. Bozza et al., "Electron/pion separation with an Emulsion Cloud Chamber by using a Neural Network," *Journal of Instrumentation*, vol. 2, Article ID P02001, 2007.

[118] M. De Serio, M. Ieva, S. Simone et al., "Momentum measurement by the angular method in the Emulsion Cloud Chamber," *Nuclear Instruments and Methods in Physics Research A*, vol. 512, no. 3, pp. 539–545, 2003.

[119] N. Armenise, M. De Serio, M. Ieva et al., "High-speed particle tracking in nuclear emulsion by last-generation automatic microscopes," *Nuclear Instruments and Methods in Physics Research A*, vol. 551, no. 2-3, pp. 261–270, 2005.

[120] S. Balestra, A. Bertolini, C. Bozza et al., "A fast automatic plate changer for the analysis of nuclear emulsions," *Nuclear Instruments and Methods in Physics Research A*, vol. 716, pp. 96–100, 2013.

[121] T. Fukuda, K. Kodamab, M. Komatsu et al., "The analysis of interface emulsion detector for the OPERA experiment in JAPAN Scanning facility," *Journal of Instrumentation*, vol. 5, Article ID P04009, 2010.

[122] N. Agafonova, A. Aleksandrov, O. Altino et al., "Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam," *Physics Letters B*, vol. 691, no. 3, pp. 138–145, 2010.

[123] G. De Lellis, "New results from the OPERA experiment," CERN Seminar, 2013.

[124] N. Agafonova, A. Aleksandrov, A. Anokhina et al., "New Results on $\nu_\mu \rightarrow \nu_\tau$ appearance with the OPERA experiment in the CNGS beam," 2013, http://arxiv.org/abs/1308.2553.

[125] N. Agafonova, A. Aleksandrov, A. Anokhina et al., "Search for $\nu_\mu \rightarrow \nu_e$ oscillations with the OPERA experiment in the CNGS beam," *Journal of High Energy Physics*, vol. 07, article 004, 2013.

[126] T. Adam, N. Agafonova, A. Aleksandrov et al., "Measurement of the neutrino velocity with the OPERA detector in the CNGS beam," *Journal of High Energy Physics*, vol. 10, article 093, 2012.

[127] T. Adam, N. Agafonova, A. Aleksandrov et al., "Measurement of the neutrino velocity with the OPERA detector in the CNGS beam using the 2012 dedicated data," *Journal of High Energy Physics*, vol. 01, article 153, 2013.

[128] S. Bertolucci, "Neutrino speed: a report on the ν_μ speed measurements of the BOREXINO, ICARUS and LVD experiments with the CNGS beam," *Nuclear Physics B*, vol. 235-236, pp. 289–295, 2013.

[129] M. Antonello, B. Baibussinov, P. Benetti et al., "Experimental search for the LSND anomaly with the ICARUS detector in the CNGS neutrino beam," *The European Physical Journal C*, vol. C73, p. 2345, 2013.

[130] F. Pietropaolo, "Status of the ICARUS experiment," *Nuclear Physics B*, vol. 235-236, pp. 115–121, 2013.

[131] T. Nakaya, "Results and prospects of the T2K neutrino experiment," Conference: C11-10-24.1, Proceedings, p. 64, http://www.worldscientific.com/doi/abs/10.1142/9789814412322 0007.

[132] K. Abe, N. Abgrall, H. Aihara et al., "Evidence of electron neutrino appearance in a muon neutrino beam," *Physical Review D*, vol. 88, no. 3, 41 pages, 2013.

[133] K. Abeaw, N. Abgrall, H. Aihara et al., "The T2K experiment," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 659, no. 1, pp. 106–135, 2011.

[134] K. Abe, N. Abgrall, Y. Ajima et al., "First muon-neutrino disappearance study with an off-axis beam," *Physical Review D*, vol. 85, Article ID 031103, 8 pages, 2012.

[135] T. Kobayashi, "T2K experiment," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[136] L. A. Corwin, "(Status of NOνA)," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[137] C. Athanassopoulos, L. B. Auerbach, R. L. Burman et al., "Results on $\nu_\mu \rightarrow \nu_e$ neutrino oscillations from the LSND experiment," *Physical Review Letters*, vol. 81, no. 9, pp. 1774–1777, 1998.

[138] A. Aguilar, L. B. Auerbach, R. L. Burman et al., "Evidence for neutrino oscillations from the observation of $\overline{\nu}_e$ appearance in a $\overline{\nu}_\mu$ beam)," *Physical Review D*, vol. 64, no. 11, Article ID 112007, 22 pages, 2001.

[139] B. Armbruster, I. M. Blair, B. A. Bodmann et al., "Upper limits for neutrino oscillations $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ from muon decay at rest," *Physical Review D*, vol. 65, no. 11, Article ID 112001, 16 pages, 2002.

[140] A. A. Aguilar-Arevalo, C. E. Anderson, S. J. Brice et al., "Event Excess in the MiniBooNE Search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations," *Physical Review Letters*, vol. 105, no. 18, Article ID 181801, 5 pages, 2010.

[141] X.-Q. Li, Y. Liu, Z.-T. Wei, and L. Tang, "Neutrino decay as a possible interpretation of the MiniBooNE observation with unparticle scenario," *European Physical Journal C*, vol. 56, no. 1, pp. 97–103, 2008.

[142] M. Maltoni and T. Schwetz, "Sterile neutrino oscillations after first MiniBooNE results," *Physical Review D*, vol. 76, no. 9, Article ID 093005, 2007.

[143] G. Mention, M. Fechner, Th. Lasserre et al., "The Reactor Antineutrino Anomaly," *Physical Review D*, vol. 83, no. 7, Article ID 073006, 20 pages, 2011.

[144] C. Giunti and M. Laveder, "Statistical significance of the gallium anomaly," *Physical Review C*, vol. 83, no. 6, Article ID 065504, 2011.

[145] A. C. Hayes, J. L. Friar, G. T. Garvey, and G. Jonkmans, "Reanalysis of the reactor neutrino anomaly," http://arxiv.org/abs/1309.4146.

[146] C. Giunti, M. Laveder, Y. F. Li, and H. W. Long, "A Pragmatic view of short-baseline neutrino oscillations," *Physical Review D*, vol. 88, no. 7, 6 pages, 2013.

[147] S. Razzaque and A. Y. Smirnov, "Searching for sterile neutrinos in ice," *Journal of High Energy Physics*, vol. 1107, article 084, 2011.

[148] G. Bellini, J. Benziger, D. Bick et al., "SOX: short distance neutrino Oscillations with BoreXino," *Journal of High Energy Physics*, vol. 1308, article 038, 2013.

[149] P. Bernardini, A. Bertolin, C. Bozza et al., "Prospect for charge current neutrino interactions measurements at the CERN-PS," http://arxiv.org/abs/1111.2242.

[150] M. Antonello, D. Bagliani, B. Baibussinov et al., "Search for anomalies in the neutrino sector with muonspectrometers and large LArTPC imaging detectors at CERN," http://arxiv.org/abs/1208.0862.

[151] M. Antonello, D. Bagliani, B. Baibussinov et al., "Search for anomalies from neutrino and anti-neutrino oscillations at $\Delta m^2 \sim 1\mathrm{eV}^2$ with muon spectrometers and large LArTPC imaging detectors," http://arxiv.org/abs/1203.3432.

[152] A. B. Sousa, "MINOS search for sterile neutrinos," *Journal of Physics: Conference Series*, vol. 408, no. 1, Article ID 012026, 2013.

[153] M. C. Gonzalez-Garcia and M. Maltoni, "Atmospheric neutrino oscillations and new physics," *Physical Review D*, vol. 70, no. 3, Article ID 033010, 2004.

[154] G. Battistoni, Y. Becherini, S. Cecchini et al., "Search for a Lorentz invariance violation contribution in atmospheric neutrino oscillations using MACRO data," *Physics Letters B*, vol. 615, no. 1-2, pp. 14–18, 2005.

[155] P. Adamson, C. Andreopoulos, K. E. Arms et al., "Testing Lorentz invariance and CPT conservation with NuMI neutrinos in the MINOS near detector," *Physical Review Letters*, vol. 101, no. 15, Article ID 151601, 2008.

[156] P. A. N. MacHado, H. Nunokawa, and R. Z. Funchal, "Testing for large extra dimensions with neutrino oscillations," *Physical Review D*, vol. 84, no. 1, Article ID 013003, 2011.

[157] J. Adam, X. Bai, A. M. Baldini et al., "New constraint on the existence of the mu + − > e+ gamma decay," *Physics Review Letters*, vol. 110, Article ID 201801, 5 pages, 2013.

[158] M. G. Catanesi, E. Radicioni, R. Edgecock et al., "Large-angle production of charged pions by 3-12.9∊GeV/c protons on beryllium, aluminium and lead targets," *European Physical Journal C*, vol. 54, no. 1, pp. 37–60, 2008.

[159] K. Hiraide, J. L. Alcaraz-Aunion, S. J. Brice et al., "Search for charged current coherent pion production on carbon in a few-GeV neutrino beam," *Physical Review D*, vol. 78, no. 11, Article ID 112004, 19 pages, 2008.

[160] Y. Kurimoto, J. L. Alcaraz-Aunion, S. J. Brice et al., "Measurement of inclusive neutral current Pion production on carbon in a few-GeV neutrino beam," *Physical Review D*, vol. 81, Article ID 033004, 2010.

[161] A. Laszlo, "The NA61/SHINE experiment at the CERN SPS," *Nuclear Physics A*, vol. 830, no. 1–4, pp. 559c–562c, 2009.

[162] M. Gazdzicki, Z. Fodor, and G. Vesztergombi, "Study of hHadron production in hadron-nucleus and nucleus-nucleus collisions at the CERN SPS," SPSC-P-330; CERN-SPSC-2006-034, http://cdsweb.cern.ch/record/995681/files/.

[163] B. A. Popov, "Hadron production experiments and their implications on neutrino physics," in *International Conference on Neutrino Physics and Astrophysics*, Kyoto, Japan, 2012.

[164] T. Kafka and V. Paolone, "Prospects and status of the MINERνA experiment at FNAL," *Progress in Particle and Nuclear Physics*, vol. 64, no. 2, pp. 181–183, 2010.

[165] V. Paolone, "MINERvA: status and prospect," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[166] J. Spitz, "ArgoNeuT, a liquid argon time projection chamber in a low energy neutrino beam," *Journal of Physics: Conference Series*, vol. 203, Article ID 012108, 2010.

[167] F. Cavanna, "The ArgoNeuT LAr TPC: a dedicated experiment for cross section measurements at FNAL," in *Proceedings of the 23rd International Workshop on Weak Interactions and Neutrinos (WIN '11)*, Cape Town, South Africa, January 2011.

[168] T. Chiarusi and M. Spurio, "High-energy astrophysics with neutrino telescopes," *European Physical Journal C*, vol. 65, no. 3, pp. 649–701, 2009.

[169] A. Avrorin et al., "The Baikal neutrino experiment: results and plans," *Nuclear Instruments and Methods in Physics A*, vol. 630, pp. 115–118, 2011.

[170] M. Ackermann, J. Adams, J. Ahrens et al., "Search for ultra-high-energy Neutrinos with AMANDA-II," *The Astrophysical Journal*, vol. 675, no. 2, p. 1014, 2008.

[171] R. Abbasi, Y. Abdou, T. Abu-Zayyad et al., "Limits on a muon flux from Kaluza-Klein dark matter annihilations in the Sun from the IceCube 22-string detector," *Physical Review D*, vol. 81, no. 5, Article ID 057101, 6 pages, 2010.

[172] E. Resconi, "Neutrino telescope: IceCube," in *Proceedings of the Neutrino*, Athens, Ga, USA, 2010.

[173] S. Odrowski, "Recent results from the IceCube neutrino telescope," *Acta Physica Polonica B*, vol. 6, no. 2, p. 687, 2013.

[174] P. Amram, M. Anghinolfi, S. Anvar et al., "The ANTARES optical module," *Nuclear Instruments and Methods in Physics Research A*, vol. 484, no. 1–3, pp. 369–383, 2002.

[175] S. Adrian-Martinez, I. Al Samarai, A. Albert et al., "Search for cosmic neutrino point sources with four year data of the ANTARES telescope," *The Astrophysical Journal*, vol. 760, no. 1, p. 53, 2012.

[176] S. Adrián-Martínez, I. Al Samarai, A. Albertc et al., "Measurement of atmospheric neutrino oscillations with the ANTARES neutrino telescope," *Physics Letters B*, vol. 714, no. 2–5, pp. 224–230, 2012.

[177] P. Sapienza, "KM3NeT, Multi-Km3 neutrino telescope: perspectives," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[178] R. Abbasi, Y. Abdou, T. Abu-Zayyad et al., "A Search for a diffuse flux of astrophysical muon neutrinos with the IceCube 40-string detector," *Physical Review D*, vol. 84, no. 8, Article ID 082001, 20 pages, 2011.

[179] M. G. Aartsen, R. Abbasi, Y. Abdou et al., "Measurement of atmospheric neutrino oscillations with Ice-Cube," *Physical Review Letters*, vol. 111, no. 8, Article ID 081801, 6 pages, 2013.

[180] R. Abbasi, Y. Abdou, T. Abu-Zayyad et al., "Search for a Lorentz-violating sidereal signal with atmospheric neutrinos in IceCube," *Physical Review D*, vol. 82, no. 11, Article ID 112003, 6 pages, 2010.

[181] M. G. Aarsten, R. Abbasi, Y. Abdou et al., "Measurement of the atmospheric ν_e flux in IceCube," *Physical Review Letters*, vol. 110, no. 15, Article ID 151105, 7 pages, 2013.

[182] L. A. Fusco, "Measurement of the atmospheric ν_μ energy spectrum with the ANTARES neutrino telescope," in *ICRC Conference*, 2013.

[183] L. A. Fusco and V. Kalinowsky, "Measurement of the atmospheric ν_μ energy spectrum with the ANTARES neutrino telescope," in *ICRC Conference*, 2013.

[184] S. Biagi, "Updated limits on diffuse fluxes of cosmic neutrinos with 2008–2011 ANTARES data," http://arxiv.org/abs/1305.6442.

[185] V. Barger, D. Marfatia, and K. Whisnant, "Breaking eightfold degeneracies in neutrino CP violation, mixing, and mass hierarchy," *Physical Review D*, vol. 65, no. 7, Article ID 073023, pp. 730231–7302317, 2002.

[186] G. L. Fogli, E. Lisi, A. Marrone et al., "A global analysis of neutrino oscillations," *Nuclear Physics B*, vol. 235-236, pp. 125–132, 2013.

[187] R. Battistoni, M. Mezzetto, P. Migliozzi, and F. Terranova, "European facilities for accelerator neutrino physics: perspectives for the decade to come," *Rivista del Nuovo Cimento*, vol. 33, no. 6, pp. 313–343, 2010.

[188] T. Nakaya, "Hyper-kamiokande," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[189] C. Walter, "Atmospheric neutrinos: overview and opportunities," in *Proceedings of the 16th Workshop on Neutrino Telescopes*, Venezia, Italy, 2013.

[190] R. N. Mohapatra, "Neutrinos and the LHC," in *Proceedings of the Neutrino*, Athens, Ga, USA, 2010.