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EXPERIMENTAL REVIEW OF ATMOSPHERIC NEUTRINO OSCILLATIONS

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Abstract

A short review of the atmospheric neutrino experiments is given. The main enphasis is placed on SuperKamiokande, Soudan-2 and MACRO.

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1 INTRODUCTION

Atmospheric neutrinos are produced in the cascade originated in the atmosphere by a primary cosmic ray. Underground detection of atmospheric neutrino-induced events was pioneered by the Kolar Gold Field KGF[1] experiment in India and the CWI2[2] experiment in a mine in South Africa. The field gained new interest when the large underground detectors for proton decay experiments were put in operation. Initially atmospheric neutrinos were studied mainly as possible sources of backgrounds for proton decay searches, but it was very soon discovered with the water Cherenkov experiments, IMB in the United States and Kamiokande in Japan, that the ratio between events with a muon and those with an electron was lower than expected.

The first historical observation of the anomaly was in 1986 in the IMB paper "Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon Decay Search"[3]. It was observed in this paper that "The simulation predicts that $34\% \pm 1\%$ of the events should have an identified muon decay while our data has $24\% \pm 3\%$". The importance of this discrepancy as possible signature for neutrino oscillations in the path length between the production point and the detector (in the range 10 -13000 km) was not fully recognized at the outset. 1988[5] saw the first paper by the Kamiokande collaboration dedicated to this anomaly, followed by two papers from the IMB collaboration[4].

However, this anomaly was not confirmed by the proton decay iron fine-grained experiments NUSEX[6] (in the Mont Blanc tunnel between France and Italy) and Frejus[7] (in another tunnel under the Alps) and it was suggested that the anomaly was due to the differences in the neutrino cross sections in water and iron not taken into account in the Fermi gas model used in the original calculations. A calculation by Engel[8] showed that this effect should be negligible for the energies in question. Later, the results from another fine-grained iron detector Soudan-2[9] showed that there was probably a statistical fluctuation in the NUSEX and Frejus data.

In 1994 another anomaly was observed with the Kamiokande experiments[10], namely the distortion of the angular distribution of the events with a single muon in the so-called internally produced Multi-GeV data sample with a reduction of the flux of the vertical up-going events.

There were several attempts to look for possible angular distortion in other categories of events, for example in the neutrino externally produced upward-going muons. Results were produced at that time by the IMB experiment[11], the Baksan[12] experiment in the URSS and the Kamiokande experiment itself[13]. The results were inconclusive or in contradiction with the neutrino oscillation hypothesis, particularly as far as analysis of the stopping muon/ through-going muon ratio in the IMB experiment[11] is concerned.

The MACRO tracking experiment in the Gran Sasso laboratory began the operation for neutrino physics in 1989 with a small fraction of the final detector. The first results of MACRO[14] in 1995 showed that there was a deficit of events, particularly in the vertical direction. However the statistics did not at that time suffice to discriminate unambiguously between the oscillation and the no-oscillation hypothesis.

Another big step forward in this field was due to the Superkamiokande experiment. In 1998 at the Takayama Neutrino conference there announcement was made of the observation of neutrino oscillation (ν_μ disappearance) from the Superkamiokande experiment. It is notable that, at the same conference, the two other running experiments Soudan-2 and MACRO presented results in strong support of the same ν_μ oscillations pattern observed by SuperKamiokande[15].

2 NEUTRINO OSCILLATIONS AND MATTER EFFECT

Neutrino oscillations[16] were suggested by B. Pontecorvo in 1957 after the discovery of the $K^0 \leftrightarrow \overline{K^0}$ transitions.

If neutrinos have masses, then a neutrino of definite flavor, ν_ℓ, is not necessarily a mass eigenstate. By analogy to the quark sector the ν_ℓ could be a coherent superposition of mass eigenstates.

The fact that a neutrino of definite flavor is a superposition of several mass eigenstates, whose differing masses M_m cause them to propagate differently, leads to neutrino oscillations : the transformation in vacuum of a neutrino of one flavor into one of a different flavor as the neutrino moves through empty space. The amplitude for the transformation $\nu_\ell \to \nu_{\ell'}$ is given by:

$$A(\nu_\ell \to \nu_{\ell'}) = \sum_m U_{\ell m} e^{-i\frac{M_m^2}{2}\frac{L}{E}} U^*_{\ell' m} \tag{1}$$

where U is a 3×3 unitary matrix in the hypothesis of the 3 standard neutrino flavors $(\nu_\mu, \nu_e, \nu_\tau)$. Adding a sterile neutrino[17] U is a 4×4 unitary matrix.

The probability $P(\nu_\ell \to \nu_{\ell'})$ for a neutrino of flavor ℓ to oscillate in vacuum into one of flavor ℓ' is then just the square of this amplitude. For two neutrino oscillations and in vacuum:

$$P(\nu_\ell \to \nu_{\ell'\neq\ell}) = \sin^2 2\theta \, \sin^2\left[1.27\,\delta M^2 \frac{L}{E}\right] \tag{2}$$

$$\delta M^2(\mathrm{eV}^2), L(\mathrm{km}), E(\mathrm{GeV})$$

This simple relation should be modified when a neutrino propagates through matter and when there is a difference in the interactions of the two neutrino flavors with matter[18].

The neutrino weak potential in matter is:

$$V_{\mathrm{weak}} = \pm\frac{G_F n_B}{2\sqrt{2}} \times \begin{cases} -2Y_n + 4Y_e & \text{for } \nu_e, \\ -2Y_n & \text{for } \nu_{\mu,\tau}, \\ 0 & \text{for } \nu_s, \end{cases} \tag{3}$$

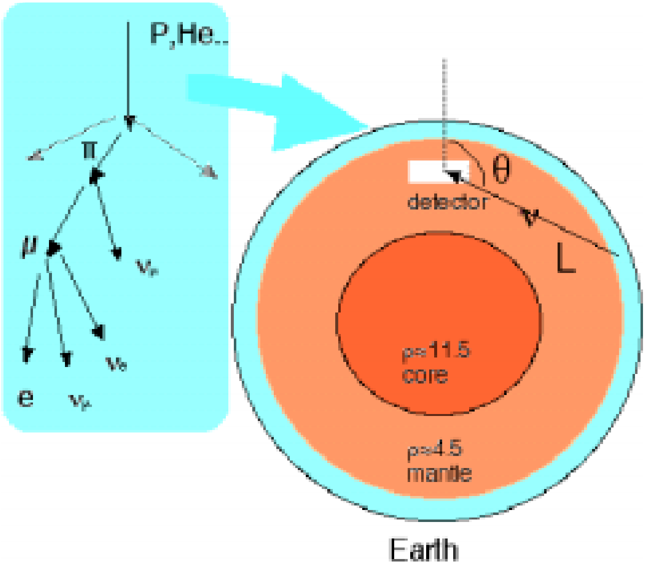

Figure 1: Sketch of atmospheric neutrino production in the atmosphere and of the detection in an underground detetector. L is the neutrino path length and θ the zenith angle.

where the upper sign refers to neutrinos, the lower sign to antineutrinos, G_F is the Fermi constant, n_B the baryon density, Y_n the neutron and Y_e the electron number per baryon (both about 1/2 in normal matter). Numerically we have

$$\frac{G_F n_B}{2\sqrt{2}} = 1.9 \times 10^{-14}\ \mathrm{eV}\ \frac{\rho}{\mathrm{g\ cm^{-3}}}. \tag{4}$$

The weak potential in matter produces a phase shift that could modify the neutrino oscillation pattern if the oscillating neutrinos have different interactions with matter. The matter effect could help to discriminate between different neutrino channels. According to equation 3, the matter effect on the Earth could be important for $\nu_\mu \to \nu_e$ and for the $\nu_\mu \to \nu_s$ oscillations, while for $\nu_\mu \to \nu_\tau$ oscillations there is no matter effect. For some particular values of the oscillation parameters the matter effect could enhance the oscillations originating "resonances" (MSW effect)[18]. The internal structure of the Earth could have an important role in the resonance pattern However, for maximum mixing, the only possible effect is reduction of the amplitude of oscillations.

3 ATMOSPHERIC NEUTRINOS

In the hadronic cascade produced from the primary cosmic ray we have the production of neutrinos with the following basic scheme :

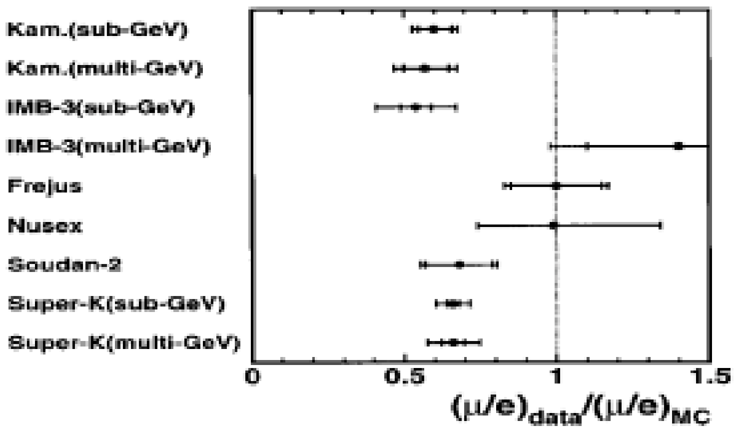

Figure 2: Measurements of the atmospheric neutrino flavor ratio.

p+n $\longrightarrow \pi + K..$
$\pi/k \longrightarrow \mu^+(\mu^-) + \nu_\mu\ (\overline{\nu}_\mu)$
$\mu^+(\mu^-) \longrightarrow e^+(e^-) + \nu_e(\overline{\nu_e}) + \overline{\nu_\mu}(\nu_\mu)$

From these decay channels we should expect at low energies about twice as many muon neutrinos as electron neutrinos. This result shows no great change with detailed calculation. Calculation of the absolute neutrino fluxes is a more complicated matter, with several sources of uncertainty[19] due to the complicated shower development in the atmosphere and to the large uncertainties in the cosmic ray spectrum. Typical uncertainties in the calculations are about 20% for absolute fluxes, 5% for the ratio between muon neutrino and electron neutrino and a few percent in the shapes of the angular distributions.

There are two basic topologies of neutrino induced events in a detector: internally produced events and externally produced events. The internally produced events have neutrino interaction vertices inside the detector. In this case all the secondaries can be observed in principle. The range of neutrino energies involved goes from a fraction of GeV up to 10 GeV or more. Both electron neutrinos and muon-neutrinos can be detected. The externally produced events have neutrino interaction vertex in the rock below the detector. Typical neutrino energies involved are of the order of 100 GeV. Only muon neutrinos can be detected. Figure 1 shows the basic geometrical factors of neutrino production and detection in an underground detector.

The neutrino events could have background connected with the production of hadrons by photoproduction due to the down-going muons. This background was measured with the MACRO experiment[20]. The photoproduced neutrons can simulate internal events and the pions can simulate stopping or through-going muons. The rate of this background depends on the rate of the down-going muons and there-

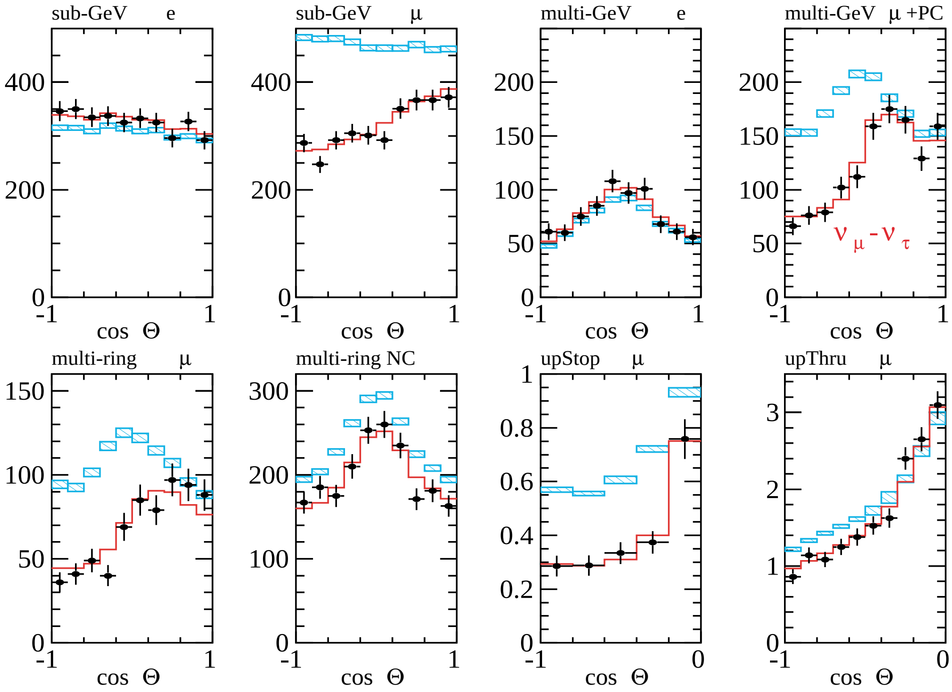

Figure 3: Zenith angle distributions in SuperKamiokande for electron and muons and in different topologies [28].

fore on the depth. This effect could be important for detectors of shallow depth and it could be one of the reason for some past results in contrast with the current oscillation scenario.

4 The SuperKamiokande experiment

There is no room here to describe all the impressive amount of data coming form the SuperKamiokande detector, I will summarize only a few points: for a full review see[21][22]. There can be no question that this detector has produced the world-wide best data concerning atmospheric neutrinos. This has been very recently recognized with the Nobel prize awarded to M. Koshiba (even though the official motivation is related to neutrinos from SN1987A). The main strength of the Superkamiokande data is related to the different topologies detected: electron neutrino events internally produced and muon neutrino events, internally or externally produced.

Figure 2 s the Superkamiokande results concerning the flavor ratio together with the results of other experiments. This result shows clearly that there is a deficit of muon neutrinos as compared to electron neutrinos.

Figure 3 shows the angular distribution for sub-GeV events ($Evis < 1.33GeV$) and multi-GeV ($Evis > 1.33GeV$ corresponding to an electron momentum of 1.33 GeV/c or a muon momentum of 1.4 GeV/c. The solid histogram shows the prediction for no oscillation while the dashed histogram shows the prediction with

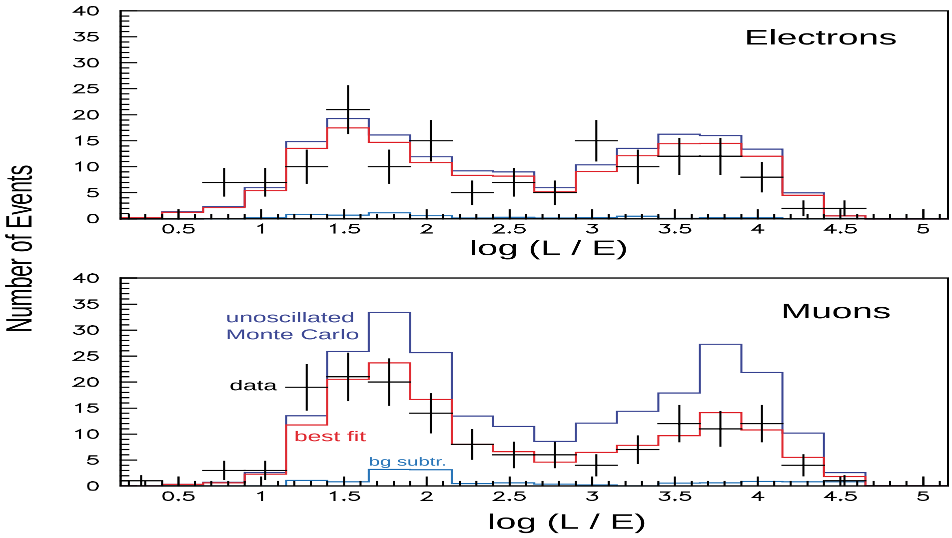

Figure 4: The L/E distribution in Soudan-2 [23]

neutrino oscillations for the best fit point. The distortion of the angular distribution and the up/down asymmetry in the muon samples could not be explained due to uncertainty in the atmospheric flux calculations, which are mainly on the total flux. Similar effects have been observed by SuperKamiokande in the category of the Upward through-going muons and of the Upward stopping muons.

The current data are in favor of the $\nu_\mu \to \nu_\tau$ oscillations with maximul mixing. The best fit of the overall data gives $\chi^2 = 163.2/170\ dof$ for $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and $\sin^2 2\theta = 1.0$ while $\chi^2 = 456.5/172\ dof$ for no-oscillations.

Finally, using the matter effects in the category Upward through-going muons and data samples enriched in neutral current events the hypothesys of a fraction of oscillation in ν_s was tested. The fraction of $\nu_\mu \to \nu_\tau$ probability is defined as: $\nu_\mu \to cos\xi \cdot \nu_\tau + sin\xi \cdot \nu_{sterile}$. The limit on $\nu_\mu \to \nu_{sterile}$ is $sin^2\xi < 0.19$ at 90% C.L..

Superkamionade also has a weak indication that the number of upward going τ enriched events is larger than the number of down-going events.

5 Soudan -2

Soudan-2 is an iron tracking calorimeter of total mass 963 tons. The results of the Soudan-2 experiment are discussed in detail in the proceedings of the neutrino 2002 conference[23]. Here I wish to stress the importance of this experiment for the Sub-GeV events (events having energies of the order of 1 GeV or less), where possible contradiction between the iron sampling calorimeters and the water Cherenkov detector was suggested in the past.

The Soudan-2 group has been able to study the L/E distribution for a sample of events selected to have high energy resolution (HiRes events). For this sample of events they have a resolution in log(L/E) of about 0.5. They use a quasi-elastic

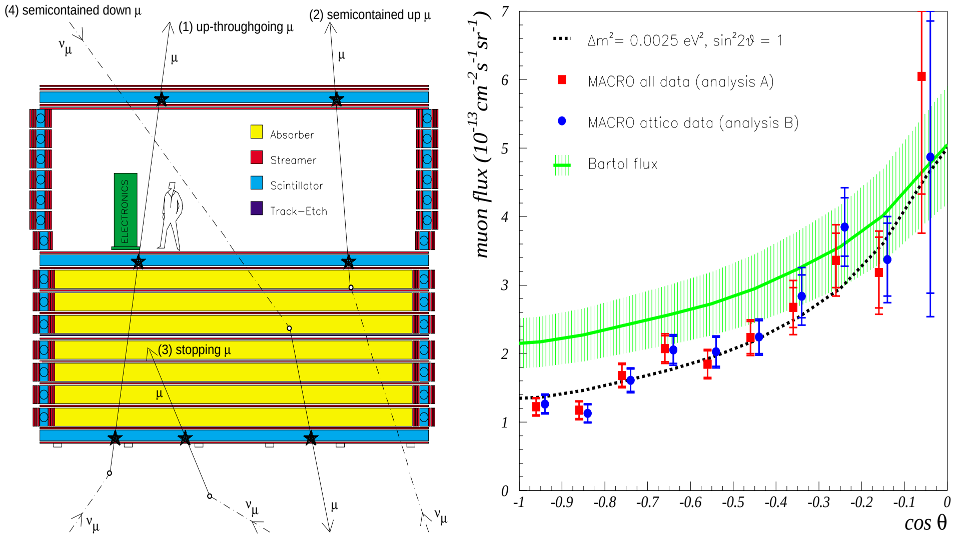

Figure 5: *MACRO: (A) Atmospheric ν-induced event topologies. (B) Upward-throughgoing muon flux (the results of two different analyses are shown).*

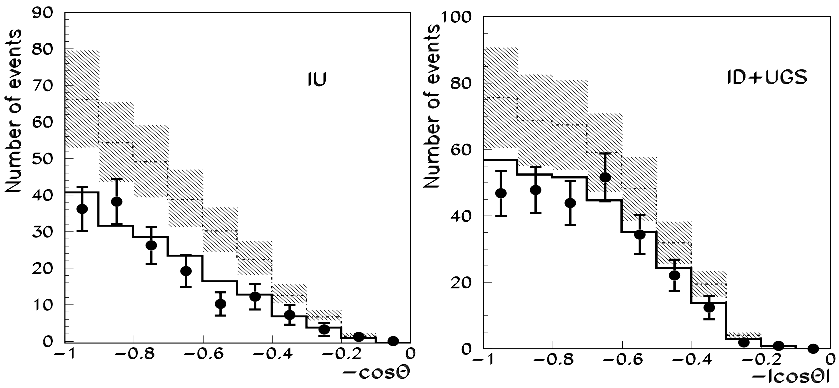

Figure 6: *Angular distributions for samples (2) and (3+4) in MACRO.*

track or shower event provided that the recoil proton is measured and that P_{lept} exceeds 150 MeV/c; otherwise, if the recoil nucleon is not visible, they require the single lepton to have E_{vis} greater than 600 MeV. They also select multiprong events, provided they are energetic (E_{vis} greater than 700 MeV) and have vector sum of P_{vis} exceeding 450 MeV/c (to ensure clear directionality). Additionally, the final state lepton momenta are required to exceed 250 MeV/c. Figure 4 shows the best agreement found at $\Delta m^2 = 1 \times 10^{-2} eV^2$ and $\sin^2 2\theta = 0.97$. The 90% confidence interval includes, however, the Superkamiokande preferred value.

6 MACRO as an atmospheric neutrino detector

The MACRO detector was located in the Gran Sasso underground laboratory [27].

The data taking started in March 1989 (with partial configurations of the apparatus) and stopped in December 2000. The active elements were liquid scintillator counters for time measurement ($\sigma \sim 0.5\,ns$) and streamer tubes for tracking($\sigma < 1°$).

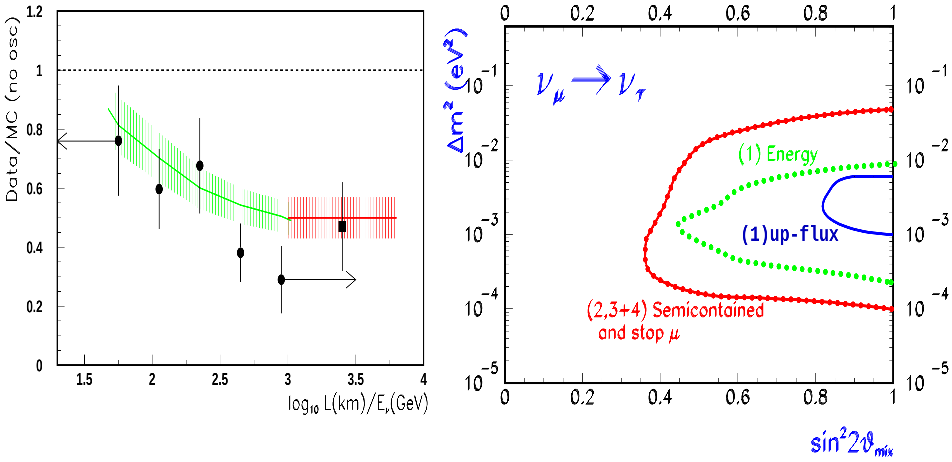

Figure 7: *MACRO: (A) Data on simulation ratio vs L/E_ν (energy estimate based on Multiple Coulomb Scattering). The curve is obtained assuming $\nu_\mu \rightarrow \nu_\tau$ oscillation. (B) Allowed regions assuming $\nu_\mu \rightarrow \nu_\tau$ oscillation.*

Thanks to its large area, fine tracking granularity and up-down symmetry, it was an appropiate tool for the study of upward-travelling muons and neutrino interactions in the apparatus. The different kinds of neutrino events detected by MACRO are shown in Fig. 5A : (1) upward-throughgoing muons, (2) semicontained upgoing muons, (3) upgoing stopping and (4) semicontained downgoing tracks. The sample (1) is selected by means of the Time-of-Flight (ToF) method and is due to more energetic neutrinos ($< E_\nu > \sim 50\ GeV$) producing muons also at long distances from the detector. The other samples are due to neutrinos of lower energy ($< E_\nu > \sim 4\,GeV$). The samples (3) and (4) are indistinguishable and they therefore are studied together (3+4).

In Fig.s 5B and 6 the angular measurements are shown for samples (1), (2) and (3+4), respectively. All distributions are far from the expectation assuming no oscillation. Assuming $\nu_\mu \rightarrow \nu_\tau$ oscillation the measurements become compatible with expectation. The best fit parameters are $\sin^2 2\theta_{mix} = 1$ and $\Delta m^2 = 0.0025\ eV^2$. Using the matter effect also the $\nu_\mu \rightarrow \nu_{sterile}$ oscillation was investigated looking at the shape of the measured flux of sample (1), but the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis remains more probable [25] at 99% C.L. level. By measuring the Multiple Coulomb Scattering [26] we can estimate the energy of muons in sample (1). Neutrino energies are inferred by means of Monte Carlo methods. In Fig. 7A the data/expectation ratio as a function of estimated L/E_ν is shown. The last point is due to sample (2). The combined probability of agreement with the no oscillation hypothesis is less than 10^{-4} (about 4σ), while there is a good agreement with the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis. This number is obtained excluding the the normalization of the neutrino flux.

In Fig. 7B the 90% C.L. allowed regions assuming $\nu_\mu \to \nu_\tau$ oscillation are shown. The smaller area is estimated by normalization and angular distribution of sample (1). The medium area is due to μ-energy estimate for the same sample. The larger area is deduced by (2) and (3+4) low energy samples.

7 Conclusions

There is a very large statistical evidence for neutrino oscillations, mainly in Superkamiokande, but also in MACRO (4σ) and Soudan-2. Fig. 8 shows the 90% C.L. allowed regions assuming $\nu_\mu \to \nu_\tau$ oscillation. On Novenber 2001 due to chain reaction originated from an imploded photomultiplier was destroyed 6777 Superkamiokande photomultipliers. So currently no atmospheric neutrino experiment is taking data. More precise data on neutrino oscillations are expected from the experiments with the long baseline neutrino beams (in Japan,USA and Europe). The results of the first direct neutrino beam experiment from KEK to Superkamiokande are in agreement with the results of the atmospheric neutrino experiments. For complete discussion of more complicated oscillation hypothesis see the talk by G. Fogli at this conference.

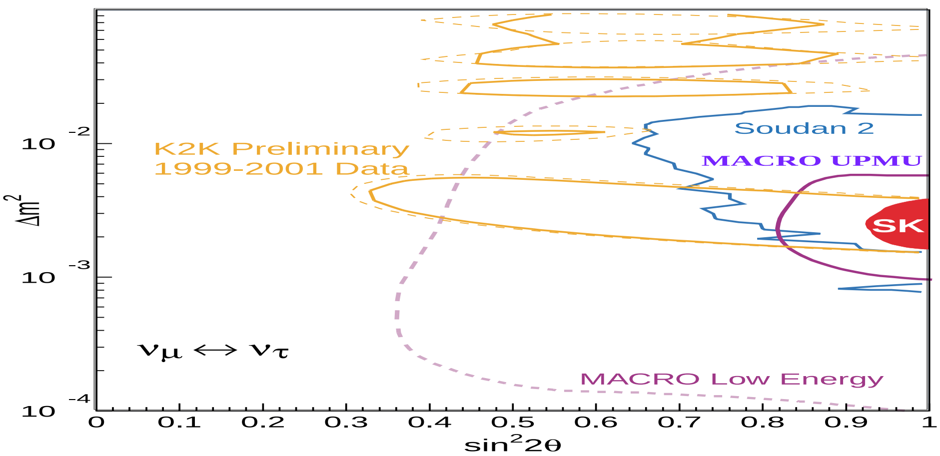

Figure 8: *90% confidence level regions assuming $\nu_\mu \to \nu_\tau$ oscillations for atmospheric neutrino experiment (Superkamiokande, Macro, Soudan-2) and the KEK long base line neutrino beam experiment[28].*

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