The properties of the tau neutrino are discussed and the recent result reporting direct detection for the first time is presented. The status of the experimental results relating to the mass of $\nu_\tau$, both from missing energy in tau decays and from neutrino oscillation experiments are reviewed. Finally, I give a perspective on future directions in studies of the physics of tau neutrinos.

1. INTRODUCTION

The tau neutrino was inferred as the third neutrino ($\nu_e$, $\nu_\mu$ and $\nu_\tau$) at the time the tau lepton was discovered and determined to be a lepton. Since that time, direct studies of the $\nu_\tau$ have proven elusive, however, due to the fact that the tau is so heavy and difficult to abundantly produce. Finally, the fact that the tau is very short lived makes the creation of an intense ‘beam’ of tau neutrinos not so simple.

Much is known about the properties of the tau neutrino despite the fact that direct detection has only been reported this past summer. In fact, that detection is clearly one of the more important results experimental results reported in high energy physics this year. I review that evidence in this presentation and a more complete talk will be given later in this workshop.

It is interesting that the $\nu_\tau$ was the last of the leptons and quarks in the three families to be observed in the laboratory, even after the top quark, which took a huge effort at Fermilab to pin down and measure the mass. The fact that the $\nu_\tau$ is the last to be detected is an indication of the experimental challenge that was involved in making the direct detection of $\nu_\tau$ interactions.

The main interest in the $\nu_\tau$ has focused on the issue of neutrino mass and oscillations. Direct mass measurements have yielded limits on the neutrino mass, while the indications are very strong that atmospheric neutrino observations indicated oscillations between the muon neutrino and the tau neutrino with a mass difference of $\Delta m^2 \sim 10^{-3}$ eV$^2$. This, of course, implies that the $\nu_\tau$ has finite mass, but undoubtedly much smaller than the limits set in the direct mass measurements.

Future developments in tau neutrino physics look quite promising. Experiments observing supernovae could lead to quite accurate mass determinations, tau neutrinos might play an important role in the interpretation of the observations of high energy cosmic rays above the Greisen, Kuzmin, Zatsepin (GKZ) bound indicating new physics.

Finally long baseline neutrino experiments will be able to study the role of the tau neutrino in the atmospheric neutrino oscillations with precision, with the possibility of an even more powerful experimental probe in the future if a neutrino factory is built, offering perhaps even the possibility of observing CP violation in the neutrino sector.

2. THE NUMBER OF NEUTRINOS

The evidence that there are three families of quarks and leptons is strong. Of course we are left with the puzzle why there are the three families, as well as the problem of determining the large mass splittings between the families. The evidence for the number of standard neutrinos comes from two sources: big bang nucleosynthesis, and the accurate determination that comes from the partial widths in Z-decay measured at LEP.

2.1. Big Bang Nucleosynthesis

The earliest indications that there are a finite and small number of families in nature came from big bang nucleosynthesis.

The primordial abundances determined for $D$, $^3$He, $^4$He and $^7$Li are affected by the number of neutrinos produced in the big bang. The predictions and understanding of these abundances[1] is a major triumph of the standard big bang model of the early universe. The abundances of these light elements range over nine orders of magnitude! The first constraint on these abundances is on $Y$, the $^4$He fraction. From number of neutrons when nucleosynthesis began, we know that $Y$ is bounded, $Y < 0.25$. 
Figure 1. The abundances of light elements in nucleosynthesis, which vary by a factor of $10^9$ are shown. The parameter $\eta$ is the baryon to photon ratio $x10^{10}$, which is not well determined.

The observed value of $Y$ (figure 1) is

$Y_{\text{observed}} = 0.238 \pm 0.002 \pm 0.005$

The presence of additional neutrinos would at the time of nucleosynthesis increases the energy density of the Universe and hence the expansion rate, leading to larger $Y$. The relation below gives the magnitude of the effect due to an additional neutrino,

$\Delta Y_{\text{BBN}} = 0.012 - 0.014 \Delta N_{\nu} \quad 1.7 < N_{\nu} < 4.3$

The most precise measurements of the number of light neutrinos come from $Z \to e^+ + e^-$ partial width measurements at LEP. The invisible partial width, $G_{\text{inv}}$, is determined by subtracting the measured visible partial widths ($Z$ decays to quarks and charged leptons) from the $Z$ width. The invisible width is assumed to be due to $N_{\nu}$, in the Standard Model, $(\Gamma_{\nu}/\Gamma)_{\text{SM}} = 1.991 \pm 0.001$, where using the ratio reduces the model dependence. Using this prediction and comparing with the accurate LEP measurements, the value [5] for the number of neutrinos is bounded by

$N_{\nu} = 2.984 \pm 0.008$

This impressive measurement gives strong credence to the view that there are three families of leptons and quarks.

3. TAU NEUTRINO EXISTENCE

The existence of the tau neutrino has relied on the indirect (though very strong) evidence until this past summer. The initial evidence was presented by Feldman et al [6] in 1981 from tau decay data. The DONUT experiment [7] at Fermilab has now reported the first direct observations of detected $\nu_{\tau}$ interactions. They observe the tau and its decays from $\nu_{\tau}$ charged current interactions.

The general principal of the DONUT experiment is to produce a strong source of tau neutrinos by interactions of the 800 GeV proton beam with a beam dump. The proton interactions produce a large number of $D_0$, having a very short lifetime and subsequently yielding $\nu_{\tau}$’s in the final state. This scheme to produce the intense beam of tau neutrinos is shown in figure 2. The data run reported used an integrated total number of protons on target of $3.6 \times 10^{17}$, and the data was taken from April to September 1997.
The total number of $\nu_\tau$ interactions is estimated to be $\sim 1100$ ($\nu_\mu$, $\nu_e$, $\nu_\tau$) for the entire DONUT data run. They found 203 candidates for $\nu_\tau$ in a total of $6.6 \times 10^6$ triggers. The reported $\nu_\tau$ events satisfied the event topology shown in figure 3, where they measure the parent tau and identify a kink. They also search for the topology were the tau is too short lived to emerge from the 1 mm steel absorber, but they have not reported on that topology. In that case, they do not measure the parent tau but identify the candidates by the apparent kink when the track is projected back toward the vertex.

![Figure 3. The event topology signature for observing tau neutrino interactions in the DONUT experiment. The parent tau is indentified and the kink from the subsequent tau decay is observed and measured using nuclear emulsions.](image)

The final experimental challenge is ‘proving’ that the observed events are due to tau neutrino interactions and not background events satisfying the topological requirements. Detailed tests and modeling has been done to understand the backgrounds, as well as characterizing measured parameters that can at least statistically distinguish tau neutrino events from background. Background events can come from various sources like overlapping events (randomly associated tracks) that fake this topology, scattering of a track to look like a kink or reconstructed charm events $D^+$ decays without the lepton identified. Fig. 4 illustrates the $p_T$ distribution of both ‘signal’ events and the candidates identified as background events. As a result of a detailed analysis of the candidate events, their final result is summarized below.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\tau$ events observed</td>
<td>4</td>
</tr>
<tr>
<td>Expected</td>
<td>$4.1 \pm 1.4$</td>
</tr>
<tr>
<td>Background</td>
<td>$0.41 \pm 0.15$</td>
</tr>
</tbody>
</table>

![Figure 4. The $p_T$ distribution of candidate events, where the events identified as $\nu_\tau$ events typically have larger $p_T$.](image)

### 4. TAU NEUTRINO PROPERTIES

#### 4.1 Spin of the $\nu_\tau$

The spin of the $\nu_\tau$ has been established [5] as $J = 1/2$. The possibility of $J = 3/2$ has been ruled out by establishing that the $\rho^-$ is not in a pure $H \pm -1$ helicity state in the decay $\tau^- \to \rho^- + \nu_\tau$.

#### 4.2 Magnetic Moment of $\nu_\tau$

We expect $m_a = 0$ for Majorana or chiral massless Dirac neutrinos. If $SU(2) \times U(1)$ is extended to include massive neutrinos,

$$\mu_\nu = 3eG_Fm_\nu \left( \frac{m_e^2}{(8\pi^2/\sqrt{2})} \right) = \left( 3.20 \times 10^{-19} \right) m_\nu \mu_B$$

where $m_\nu$ is in eV and $\mu_B = eh/2m_e$ Bohr magnetons. Using the upper bound $m_\tau < 18$ MeV, one obtains $m_\nu < 0.6 \times 10^{11}$ m$_B$. This should be compared to the experimental limit of $m_\nu < 5.4 \times 10^7$ m$_B$ from $\nu_\tau + e^- \to \nu_\tau + e^-$ scattering as measured in BEBC.

#### 4.3 Electric Dipole Moment of the $\nu_\tau$

The electric dipole moment of the $\nu_\tau$ has been established as $< 5.2 \times 10^{-17}$ e cm from $\Gamma (Z \to ee)$ at LEP.
4.4 \( \nu \tau \) Charge
The charge of the \( n_t \) has been determined to be \( < 2 \times 10^{-14} \) from the Luminosity of Red Giants [8]

4.5 \( \nu \tau \) Lifetime
The \( \nu \tau \) lifetime has been determined to be \( > 2.8 \times 10^{15} \text{ sec/eV} \) Astrophysics for \( m_\nu < 50 \text{ eV} \) [9]

4.6 Direct Mass Measurement of \( \nu \tau \)
Direct bounds on the \( \nu \tau \) mass come from reconstruction of \( \tau \) multi-hadronic decays. The best limits come from the Aleph experiment at LEP studying the reactions [10]:

\[ \tau^- \rightarrow 2\pi + \pi^+ + \nu_\tau \]

they set a limit of \( m_\tau < 22.3 \text{ MeV} \) from a total of 2939 events.

\[ \tau^- \rightarrow 3\pi + 2\pi^+ + (\pi^0) + \nu_\tau \]

they set a limit of \( m_\tau < 21.5 \text{ MeV/c}^2 \) from 52 events.

The combined limit is

\[ m_\tau < 18.2 \text{ MeV/c}^2 \]

The method is to analyze event topologies having very little Q-value phenomenologically as two body decays

\[ \tau (E_\tau, p_\tau) \rightarrow h (E_h, p_h) + \nu_\tau (E_\nu, p_\nu) \]

In the tau rest frame, the hadronic energy is

\[ E_h^* = (m_\tau^2 + m_h^2 + m_\nu^2) / 2m_\tau \]

In the laboratory frame

\[ E_h = \gamma (E_h^* + \beta p_h^* \cos \theta) \]

interval bounded for different \( m_\nu \)

\[ E_h^{\text{max, min}} = \gamma (E_h^* \pm \beta p_h^*) \]

Figure 5 illustrates two sample events superposed on the kinematical limits for different neutrino masses illustrating how the events limit the neutrino mass.

![Figure 5](image5.png)

**Figure 5.** Two sample events from the reaction \( \tau^- \rightarrow 3\pi + 2\pi^+ + (\pi^0) + \nu_\tau \) with the error contours to be compared with the kinematic limits for different neutrino masses.

![Figure 6](image6.png)

**Figure 6.** The reconstructed events from Aleph for the reaction displayed on top of the kinematical limits for \( m_\nu = 0 \) (shaded) and \( m_\nu = 23 \text{ MeV} \) (line).

The likelihood fit for all the events from the reaction \( \tau^- \rightarrow 5\pi (\pi^0) \nu_\tau \) is shown in Fig 7 yielding a 90% confidence limit of \( ~ 23 \text{ MeV} \).
5. NEUTRINO OSCILLATIONS

5.1 Introduction to Neutrino Oscillations

Neutrino oscillations were first suggested by B. Pontecorvo in 1957 after the discovery of oscillations in the kaon sector. If neutrinos have mass, then a neutrino of definite flavor, $\nu_t$, is not necessarily a mass eigenstate. In analogy to the quark sector the $\nu_t$ 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 $\nu_i \rightarrow \nu_f$ is given by:

$$A(\nu_i \rightarrow \nu_f) = \sum_m U_{im} e^{-\frac{M_m^2 L}{2 E}} U_{fm}^*$$

where $U$ is a 3 x 3 unitary matrix in the hypothesis of the 3 standard neutrino flavors ($\nu_e, \nu_\mu, \nu_\tau$). In the hypothesis of a sterile neutrino $U$ is a 4 x 4 unitary matrix.

The probability $P(\nu_i \rightarrow \nu_f)$ for a neutrino of flavor $i$ to oscillate in vacuum into one of flavor $f$ is then just the square of this amplitude. For two neutrino oscillations and in vacuum:

$$P(\nu_i \rightarrow \nu_f) = \sin^2 2\theta \sin^2 \left(1.278 M^2 \frac{L}{E} \right)$$

Where $\delta M^2$ is in $eV^2$, $L$ in $km$ and $E$ in $GeV$. Figure 8 shows the oscillation phenomena as a function of the parameter $L/E$. The example chosen is for $\Delta m^2 = 3 \times 10^{-3} eV^2$, which is the nominal value for the neutrino oscillation solutions to the atmospheric neutrino data described below. Note that the probability is $P = \frac{1}{2}$ for large values of $L/E$ and the most sensitive regime to see the effect of neutrino oscillations is when $L/E \sim 1/\Delta m^2$. These parameters are important in the discussion of atmospheric neutrinos below, and the distance chosen for the next generation long baseline neutrino experiments.

$$P(\nu_i \rightarrow \nu_f) = \sin^2 2\theta \sin^2 \left(1.278 M^2 \frac{L}{E} \right)$$

Figure 8. Neutrino oscillation phenomena for various values of $L/E$ using $\Delta m^2 = 3 \times 10^{-3} eV^2$.

This simple relation should be modified when there is a difference in the interactions of the two neutrino flavors with matter. The neutrino weak potential in matter is:

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

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 $Y$, the electron number per baryon (both about 1/2 in normal matter). Numerically we have

$$\frac{G_F n_B}{2\sqrt{2}} = 1.9 \times 10^{-14} \text{eV} \frac{\rho}{\text{gcm}^{-3}}$$

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 the equation above the matter effect in the Earth could be important for $\nu_\mu \rightarrow \nu_e$ and for the $\nu_\mu \rightarrow \nu_x$ oscillations, while for $\nu_\tau \rightarrow \nu_x$ 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). The internal structure of the Earth could have an important role in the resonance pattern. However, for maximum mixing, the only possible effect is the reduction of the amplitude of oscillations.

$$\frac{G_F n_B}{2\sqrt{2}} = 1.9 \times 10^{-14} \text{eV} \frac{\rho}{\text{gcm}^{-3}}$$

5.2 Atmospheric Neutrinos

There are several indications for neutrino oscillations, which are indicated in Fig. 9 [11]. However for the purpose of this presentation, which addresses the physics of the tau neutrino, the pertinent data is that on atmospheric neutrinos, which provide evidence for finite $\nu_\tau$ mass, and a mass difference between the tau neutrino and the muon neutrino of about $10^{-3}$ eV$^2$. Below I review the status of the evidence in atmospheric neutrinos and the implications for the tau neutrino.

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

$$P + \text{Nucleus} \rightarrow \pi^+'s + K's + \text{nucleons}$$

$$\pi(K) \rightarrow \mu + \nu_\mu$$

$$\mu \rightarrow e + \nu_\mu + \nu_e$$

From these decay channels one expects at low energies approximately twice as many muon neutrinos as electron neutrinos. Detailed corrections do not change this expectation appreciably. The calculation of the absolute neutrino fluxes is more difficult, with uncertainties due to the complicated shower development in the atmosphere, uncertainties in the cosmic ray spectrum and to uncertainties in production cross sections.

The source of atmospheric neutrinos is from collisions at the top of the atmosphere of primary cosmic rays producing secondary pions and kaons. These secondary particles either subsequently interact producing a cascade of more pions and kaons or decay into muons and neutrinos. The decay products contain a muon neutrino and a muon. Finally, the muons themselves decay and producing both a muon and an electron neutrino.

The neutrinos are detected in large underground detectors measuring both the flux and the angular distribution. The difference in path length, $L$, giving sensitivity to neutrino oscillations is from $L = 20$ km for downward neutrinos near the zenith to $L = 12700$ km for those coming directly up through the earth near the zenith. Also, those coming up near the vertical go through the core of the earth and the effect can be enhanced by matter oscillations.
Figure 10. Atmospheric neutrinos produced in the atmosphere from high energy cosmic ray collisions near the top of the atmosphere. The zenith angle both allows sampling different distances for the neutrino to oscillate and upward neutrinos through the core of the earth can undergo matter oscillations described above.

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. There are several hints for neutrino oscillations, which altogether make a strong case for finite neutrino mass.

**Hint 1:** Internal events, which are typically less than 1 GeV have been studied in many detectors. Due to the systematic difficulties mentioned above in accurately predicting the flux at these energies, the systematic errors are significantly reduced if the measured ratio of muon to electron neutrino events is measured, and in fact, usually the ratio of the ratios, $R = (\frac{\nu_\mu/\nu_e}{\text{obs}}) / (\frac{\nu_\mu/\nu_e}{\text{pred}})$, observed to predicted are given. The results are shown in Fig 11 and indicate fewer muon neutrinos than predicted from several experiments and, in particular, from the high statistics measurements. An obvious interpretation is that fewer muon neutrinos are observed because of neutrino oscillations causing some of the parent $\nu_\mu$ to 'disappear' because the neutrino has changed identity to another neutrino. As we will see, the most consistent interpretation is that the muon neutrino has oscillated into a tau neutrino.

Figure 11. Summary of the experimental results on the ‘internal events’ for atmospheric neutrinos. The results indicate significantly fewer muon neutrinos than expectations. This has been interpreted as due to the disappearance of muon neutrinos by the neutrino oscillation phenomena.

**Hint 2:** The data from internal events from the Superkamiokande experiment show an anisotropy up/down and a distortion of the angular distribution of the up-going events. Fig. 12 illustrates the path difference as a function of angle for neutrinos traversing the earth.

Figure 12. The path difference as a function of zenith angle is shown for atmospheric neutrino events.
Data from Superkamiokande, shown in Fig. 13 for the angular distribution of observed atmospheric neutrino events shows a deficit near the zenith, in agreement with the fits shown with neutrino oscillations, while the expectations without neutrino oscillations (also shown) indicate significantly more events near the zenith.

Figure 13. Angular distributions for both electron and muon neutrinos from the Superkamiokande experiment are shown. A deficit near the zenith is noted for muon neutrinos. The best fit including neutrino oscillations goes through the data, while the fit without neutrino oscillations predicts more events near the zenith.

**Hint 3.** The observed anomalies have been found in a consistent way for all energies. Atmospheric neutrinos are detected over a very wide range of energies, from sub-GeV neutrinos to neutrinos at energies of 100 GeV or higher. Since neutrino oscillations are a function of $L/E$, the consistency over energy showing the observed effect is a function of the parameter $L/E$ is a very important check. For the observations with solar neutrinos this check has not been possible, as only the integrated flux is measured above a threshold energy. It is this evidence that makes the case so strong for atmospheric neutrino oscillations, even though the phenomena was observed long after hints existed for solar neutrinos in the observed flux deficit.

The different energy atmospheric neutrinos are selected from the event topologies. As can be seen from Fig. 14, the external events peak near 100 GeV, while the internal events are less than 1 GeV.

Figure 14. The distribution of energies of detected neutrinos from different event topologies, covering a wide range of energies and allowing important consistency checks for neutrino oscillations.

The high energy data is from upward throughgoing muons resulting from neutrino interactions in the rock below the detector and sending muons up through the detector. The largest event sample of this type comes from the MACRO detector at the Gran Sasso. MACRO has observed:

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of observed events</td>
<td>642</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>35</td>
</tr>
<tr>
<td>Total events</td>
<td>607</td>
</tr>
<tr>
<td>Predictions (no oscillations)</td>
<td>825</td>
</tr>
</tbody>
</table>

For these high energy events only muon type events are observed, so it is not possible to reduce systematics by making a ratio to electron type events. The predictions have errors which have been estimated at 17%, making the deficit
about a 2σ effect. The ratio of observed data to the predictions is:

\[ R = 0.84 \pm 0.031(\text{stat}) \pm 0.033(\text{sys}) \pm 0.12(\text{flux}) \]

Where the systematic error is from the experiment and the flux error from the predictions of the atmospheric neutrino flux. Again, it is possible to also measure the angular distribution and that distribution for MACRO is shown in Fig. 15. Note that the fit to the neutrino oscillation hypothesis not only explains the deficit discussed above, but also explains the observed distortion in the angular distribution showing a deficit near the zenith.

The fits to neutrino oscillations from the different experiments, different topologies, different energies, etc are summarized in Fig 16. The data is consistent for internal contained events, partially contained events, stopping upward events and for throughgoing upward events. All are consistent with \( \nu_\mu \leftrightarrow \nu_\tau \) oscillations with maximal mixing and with \( \Delta m^2 = 3 \times 10^{-3} \text{ eV}^2 \).

These results are all determined for the two neutrino mixing case. The analysis is somewhat more complicated for three neutrino mixing and space does not permit a discussion here, but the present evidence for neutrino oscillations from solar neutrinos, atmospheric neutrinos and LSND are not consistent. An additional sterile neutrino has been suggested to reconcile all these results, but the atmospheric data disfavors that solution from the horizontal vs vertical events. So, the favored solution involves oscillation from muon neutrino to tau neutrino and providing experimental evidence that the tau neutrino mass is finite.

6. FUTURE PERSPECTIVES

6.1 Supernovae

What can be learned about the \( \nu_\tau \) from the next supernovae? If another supernovae occurs within our galaxy, potentially it could yield the best direct mass sensitivity for the tau neutrino.

Detection of the next supernovae will yield direct eV scale measurements of \( m(\nu_\mu) \) and \( m(\nu_\tau) \) from the Supernovae neutrinos [12]. Early black hole formation in the collapse will truncate neutrino production giving a sharp cutoff, which allows sensitivity to \( m(\nu_e) \approx 1.8 \text{ eV} \) for SN at 10 kpc in the Superkamiokande detector.

There is a concept for a future supernovae detector, OMNIS, that can be used to illustrate how well the mass of the tau neutrino could be addressed from a supernovae. Using the same principle of sensing the sharpness of timing cutoff, an analysis illustrated in Fig. 17 shows that from a supernovae at the center of the galaxy
one could determine the mass of the tau neutrino with a sensitivity of 6.2 MeV, which is significantly better than the limits set at LEP.

Figure 17. The cutoff due to early black hole formation in supernovae can potentially be used to determine the mass of the tau neutrino with sensitivity of about 6.2 MeV.

### 6.2 Ultra High Energy Cosmic Rays

There has been much interest generated recently by the report of observations in several detectors of cosmic rays beyond $10^{20}$ eV. These events are above the GZK cutoff where the cosmic rays are absorbed on the way to the earth. One conjecture to avoid this limit is that there are super high energy neutrinos incident on the earth and several possible mechanisms for production have been conjectured.

The follow up for these observations is the Auger experiment in Argentina, which is a very large shower array in conjunction with fluorescence detectors. This experiment should be able to confirm with good statistics the events beyond the GZK cutoff.

In the longer term, it may be possible to do the measurements with much larger acceptance from space. The idea is to put fluorescence detectors, much like in the the Utah High Res detector into space as shown in Fig 18. The detectors are mounted in spacecraft about 1000 km above the earth’s surface and having a field of view looking down on the earth of 120° and with two detectors can obtain good spatial resolution. There may be some background issues with lights from the earth and a test mission will be required before a science mission is scheduled. The plan is to do a test mission over the coming few years and possibly a joint NASA – ESA science mission in about a decade.

Figure 18. The OWL Airwatch concept is shown to mount fluorescence detectors in space (looking down) to obtain very large acceptance in order to study the highest energy cosmic rays.

Spectra of very high energy neutrinos for some possible sources that could be detected in Auger or OWL Airwatch is shown in Fig. 19. These possible sources could yield neutrinos that are experimentally accessible in the next generation of cosmic ray experiments.

Figure 19. Some conjectured sources of ultra high energy neutrinos are shown. It has been conjectured that neutrinos are the origin of the events observed beyond $10^{20}$ eV in cosmic rays.
Possible sources of ultra high energy neutrinos are from interactions of ultrahigh energy cosmic ray with 3K cosmic background radiation, neutrinos from AGNs, GRBs, etc, and Z-bursts – relic neutrinos from big bang cosmology.

It has been noted that the tau neutrino content of these ultra high energy neutrinos could be very high [14]. This is due to the short lived products of the $\nu_\tau$ giving extra neutrinos increasing the yield. The $\nu_\tau$ can be identified by the characteristic double shower events from charged current interaction + tau decay into hadrons and $\nu_\tau$ second shower has typically twice as much energy as first “double bang”. The actual flux of $\nu_\mu$ and $\nu_\tau$ are approximately equal at these energies.

6.3 Long Baseline Neutrino Experiments

Fig 20. The sensitivity of the long baseline neutrino experiments in the region of sensitivity observed for the atmospheric neutrino events.

The natural follow up of the atmospheric neutrino experiments detected in deep underground cosmic ray experiments are long baseline experiments. The idea is to control the incident beam energy and direction from an accelerator and to set $L/E$ in the region of interest for atmospheric neutrinos. Three long baseline experiments are being build: K2K (Japan; KEK to Superkamiokande); MINOS (U.S.A.; Fermilab to Soudan Mine), and Opera/Icanoe (Europe; CERN to Gran Sasso).

The first two of the these experiments (K2K and MINOS) are primarily disappearance experiments, detecting that the muon neutrino flux has been reduced in transit to the detector, and the third, ICANOE is able to do an actual appearance experiment, detecting the appearance of a tau neutrino interaction from a beam that began as muon neutrinos.

Finally, the ultimate long baseline experiment might be possible from the first stage of the proposed muon collider. The muon storage rings can create extremely intense neutrino beams, also providing the possibility of selecting muon neutrinos or anti-neutrinos. The neutrino intensity is very intense allowing long baselines that are optimized for oscillation studies.

This could be the first truly ‘international’ machine having the neutrino factory on one continent and the detector on another. It will be possible to make precision measurements of the oscillation parameters as illustrated in Fig. 21 having a baseline of 7400 km (for example Fermilab to Gran Sasso). It should also be pointed out that it may even be possible with such a machine to measure CP violation in the neutrino sector!

Figure 21. Precision measurements of neutrino oscillation parameters would be possile from a neutrino factory built as the first stage of a muon collider.

7. CONCLUSIONS

The physics of the tau neutrino [14] is becoming an experimentally accessible subject. The first evidence for direct observations of the tau neutrino by the DONUT experiment is an important milestone. The determined properties of the tau neutrino are consistent with those of the other neutrinos - $\nu_e$, $\nu_\mu$, $\nu_\tau$. Finally, neutrino
oscillations opens up a variety of new future possibilities for n in cosmology, astrophysics and future accelerators

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