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Physics Division

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Study of Inclusive Multi-Ring Events from Atmospheric Neutrinos*

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Abstract

The current analysis of atmospheric neutrinos by the Super-Kamiokande Collaboration is based only on fully-contained one-ring events and partially contained events. We show that the up-down ratio of fully-contained, inclusive, multi-ring events gives an independent test of the atmospheric neutrino anomaly, without the need for particle identification. Moreover, this class of events is rich in neutral current events and hence gives crucial information for discriminating between oscillations of ν_μ into $\nu_{e,\tau}$ and ν_s.

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1 Introduction

Recent results from the Super-Kamiokande collaboration have confirmed that the measured neutrino fluxes, produced by cosmic ray showers in the Earth's atmosphere, do not agree with expectations from theoretical calculations. An anomaly is seen in events with both low visible energy, the sub-GeV data [1], and high visible energy, the multi-GeV data [2]. The collaboration has used three event topologies to present evidence for these anomalies: fully contained (FC) 1 ring events, where the Cerenkov ring has the characteristics of an electron or muon – e-like and μ-like events; and partially contained (PC) events, which Monte Carlo calculations show have a 98% probability to be produced by a ν_μ charged current interaction. The e-like and μ-like events are studied both in the sub-GeV and multi-GeV samples, while the PC events are multi-GeV events. From the observed number of these events, the μ/e ratio, relative to Monte Carlo expectations, is measured to be $0.61 \pm 0.03 \pm 0.05$ for sub-GeV data, and $0.66 \pm 0.06 \pm 0.08$ for multi-GeV data. The uncertainties are statistical and systematic, respectively. In the sub-GeV case the μ/e ratio is the ratio of 1-ring μ-like to 1-ring e-like events, while in the multi-GeV case the numerator also includes the PC events.

The Super-Kamiokande collaboration has also measured the zenith angle distribution of these event classes, for both sub- and multi-GeV data. The e-like events were consistent with Monte Carlo expectations, while the distributions for μ-like and PC events were far from Monte Carlo expectations. Let $\rho_i(\phi)$ be the number of events of class i with visible products moving in the upward direction relative to the number of these events in the downward direction. The visible products must be moving in a cone about the vertical with half angle ϕ. These up-down ratios are important, as they are insensitive to much of the theoretical uncertainties associated with calculations of the neutrino fluxes from cosmic ray showers; however, they are only useful if there is a good angular correlation between the neutrino and the visible products of the neutrino interaction. For the multi-GeV data, the correlation between neutrino and charged lepton directions is good, with a mean of 15–20°. For the sum of μ-like and PC events, Super-Kamiokande has measured $\rho_\mu(78^o) = 0.52 \pm 0.07 \pm 0.01$, (Monte Carlo expectation: $0.98 \pm 0.03 \pm 0.02$), while from the e-like events they measure $\rho_e(78^o) = 0.84 \pm 0.13 \pm 0.02$ (Monte Carlo expectation: $1.01 \pm 0.06 \pm 0.03$), with uncertainties strongly dominated by statistics. While the measured value of ρ_e is consistent with Monte Carlo calculations, the discrepancy in ρ_μ is especially significant. For the sub-GeV data, the correlation between neutrino and charged lepton directions is much poorer – with a mean of about 60° – and the data give $\rho_\mu(53^o) = 0.69 \pm 0.08$ and $\rho_e(53^o) = 1.23 \pm 0.12$, where only statistical uncertainties are shown.

This data, together with that of previous experiments, provides substantial evidence that neutrinos produced in the atmosphere are oscillating as they traverse the Earth. The low systematic uncertainty on ρ_μ, both from theoretical calculations of the flux and from the Super-Kamiokande detector, make it clear that the survival probability for a ν_μ to traverse the Earth is substantially less than unity. We are therefore led to study other signals in the Super-Kamiokande data which could

- *Confirm oscillations with low systematic uncertainties.*

  Even though large uncertainties cancel from the μ/e ratio, several remain: the flux calculation, the charged current cross section, the neutral current cross section, the energy scale and the separation of 1-ring from multi-ring events each have systematic uncertainties of 4–6% [2]. On the other hand, it is striking that the systematic uncertainties for the up-down ratios $\rho_{e,\mu}$ are much smaller: the flux calculations, detector asymmetries and downward going muon flux each give systematic uncertainties of only 1–2% [2]. The anomaly in the ν_μ/ν_e flux ratio depends crucially on the particle identification, which has been quite convincingly tested at KEK [3], but still one would like to have a test independent of the systematic issues of particle ID.

- *Probe the flavor of the oscillation mode.*

  The measurement of ρ_μ clearly shows that ν_μ are disappearing on traversing the Earth, and hence must have oscillated into a combination of ν_e, ν_τ and ν_s (a singlet neutrino).[1] The present data strongly disfavors oscillations purely to ν_e, but does not distinguish between pure ν_τ and ν_s. A high statistics separation of the ν_τ and ν_s modes requires event classes with substantial probabilities of being produced by neutral current interactions.

In this letter we study the neutrino oscillation signal in the up-down ratio of inclusive multi-ring events, ρ_{MR}, both in the sub- and multi-GeV data. These are all events in which neutrino interactions produce two or more charged particles or photon showers which lead to identified Cerenkov rings. The theoretical systematic uncertainties are 1–2% from flux calculations, and 1–4% from cross sections, and we expect the experimental systematic uncertainties also to be small. The large number of multi-ring events ensures small statistical errors; for example, in the multi-GeV data the number of multi-ring events is very similar to the sum of the number of 1-ring μ-like and PC events, so the statistical power of ρ_{MR}^{multi} will be the same as for ρ_μ. For the sub-GeV data the angular correlation will not be as strong as for the multi-GeV case, but the multi-ring events have a higher neutral current component, so that ρ_{MR}^{sub} may have better capabilities to separate ν_τ from ν_s. This separation can also be probed via ρ_{π^0}, the up-down asymmetry of events with a single π^0, as has been proposed [4]. While such events have a higher neutral current component, a measurement of ρ_{MR}^{sub} will not require any particle identification, and will have better statistics. It has been suggested that the ν_τ and ν_s modes could be distinguished by studying the fraction of 2-ring events which result from neutral current π^o production [5]. However, this method has large uncertainties due to the uncertainties in neutrino interaction cross sections.

[1] In this letter, we suppress our theoretical prejudice against singlet neutrinos, which apparently require either a new low energy scale of physics, or a non-minimal see-saw.

2 Up-down Ratios

In this letter we present a simplified analysis for the up-down ratios $\rho_i(\phi)$. We assume that, for some choice of the cone half angle ϕ, the downward going neutrinos are essentially unoscillated, while the upward going neutrinos have completely oscillated.[2] The measured zenith angle distributions make this a reasonable assumption. We also assume that the flux ratio of neutrinos produced in the atmosphere, $r = \nu_\mu/\nu_e$, is independent of energy, at least for the energies which dominate a given class of events.[3] Then, for events of class i, which are induced by ν_e charged current, ν_μ charged current and neutral current interactions with relative probabilities f_e, f_μ and f_{NC}

$$\rho_i = f_e(P_{ee} + rP_{\mu e}) + f_\mu\left(P_{\mu\mu} + \frac{1}{r}P_{e\mu}\right) + f_{NC}(1 - P_s) \tag{1}$$

where P_{ij} is the probability for oscillation $\nu_i \to \nu_j$ and $P_s = (P_{es} + rP_{\mu s})/(1 + r)$. It is immediately apparent that, within these approximations, up-down asymmetries can only measure the combinations: $P_{ee}+rP_{\mu e}, P_{\mu\mu}+P_{e\mu}/r$ and $1-P_s$; and the latter is only probed if f_{NC} is appreciable. The oscillation probabilities satisfy unitarity constraints, $\Sigma_j P_{ij} = 1$, but the three combinations which can be measured remain independent. The fractions f_e, f_μ and f_{NC} can be obtained from the Monte Carlo results of the Super-Kamiokande collaboration, and are shown in Table 1.

In the cases of oscillations between two flavors, such as $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$, with CP conservation, the expressions for the ratio simplify drastically and involve only one parameter, $P_{\mu\mu}$. For $\nu_\mu \to \nu_\tau$ oscillations, $P_{ee} = 1$, $P_{\mu e} = P_{e\mu} = P_s = 0$, and $P_{\mu\mu} \leq 1$, giving the up-down ratio

$$\rho_i^{(\tau)} = f_e + f_\mu P_{\mu\mu} + f_{NC}. \tag{2}$$

For $\nu_\mu \to \nu_s$ oscillation, $P_{ee} = 1$, $P_{\mu e} = P_{e\mu} = 0$, $P_{\mu s} = 1 - P_{\mu\mu}$, and $P_s = rP_{\mu s}/(1 + r)$, and we find

$$\rho_i^{(s)} = f_e + f_\mu P_{\mu\mu} + f_{NC}\frac{1 + rP_{\mu\mu}}{1 + r}. \tag{3}$$

Finally, the case of $\nu_\mu \to \nu_e$ is the most complicated one. Under the assumption of the CP conservation, $P_{\mu e} = P_{e\mu} = 1 - P_{\mu\mu}$, and $P_{ee} = P_{\mu\mu}$. We have $P_s = 0$ in this case, and find

$$\rho_i^{(e)} = f_e(r - (r - 1)P_{\mu\mu}) + f_\mu\left(\frac{1}{r} + \frac{(r-1)}{r}P_{\mu\mu}\right) + f_{NC}. \tag{4}$$

In these cases, measurements of the up-down ratios for various event classes, i, should yield the same value for $P_{\mu\mu}$. Values for $P_{\mu\mu}$ extracted from $\rho_e^{sub,multi}$ and $\rho_\mu^{sub,multi}$ are

[2] Complete oscillation means that the relevant $\Delta m^2 L/E$ factors are sufficiently large that on averaging over L/E the probabilities become independent of these factors. If this is not the case, ρ_i is still given by (1), with the probabilities now understood to be suitably averaged over energy.

[3] This is a better approximation for the sub-GeV data than for the multi-GeV case. When r has significant energy dependence, the up-down ratios are still given by (1), but with r and $1/r$ suitably averaged.

	f_e	f_μ	f_{NC}	#MC	#data
Fully Contained Sub-GeV (Analysis A)					
1 ring e-like	0.88	0.02	0.10	812.2	983
1 ring μ-like	0.005	0.96	0.04	1218.3	900
multi-ring	0.24	0.43	0.33	759.2	696
Fully Contained Multi-GeV					
1 ring e-like	0.84	0.07	0.09	182.7	218
1 ring μ-like	0.005	0.99	0.005	229.0	176
multi-ring	0.30	0.55	0.15	433.7	398
Partially Contained	0.01	0.98	0.01	287.7	230

Table 1: Data and Monte Carlo results reported for 25.5 kiloton-years, 414 days of running time, by the Super-Kamiokande collaboration [1, 2], using the flux calculations of Ref.[6]. For each class of event, the first three columns give the Monte Carlo results for the fractions of the events which are induced by ν_e charged current, ν_μ charged current and neutral current interactions, the fourth column the expected number of events, and the fifth column the measured number of events.

shown in Table 2, using $r = 2.15$ for sub-GeV data, and $r = 3$ for multi-GeV data [6]. For oscillations to ν_τ or ν_s, $P_{\mu\mu}$ is essentially independent of r. For oscillations to ν_e, as r is increased from 2.5 to 3.5, the value of $P_{\mu\mu}$ varies from 0.20 to 0.32 (from ρ_μ^{multi}), and from 1.13 to 1.08 (from ρ_e^{multi}). There is good consistency for oscillations of ν_μ to ν_τ or ν_s, but oscillations to ν_e are excluded by the multi-GeV data at greater than 6σ, for any reasonable value for r.

For oscillations of ν_μ to ν_τ or ν_s, the sub-GeV data appears to give a somewhat larger value for $P_{\mu\mu}$ than does the multi-GeV data. However, the measured value of $\rho^{sub}(53^o)$ is larger than the true value, ρ_T, due to the smearing effect from the poor angular correlation of the sub-GeV data. This can be parameterized by a phenomenological parameter D: $\rho^{sub}(53^o) = \rho_T + D(1-\rho_T)$. The central values of $P_{\mu\mu}$ extracted from sub- and multi-GeV data coincide if $D \approx 1/3$. This is consistent with the quoted angular resolution for the sub-GeV data.

To measure ρ_{MR}, it is necessary to define a direction for the multi-ring events, and this can be done in many ways. In contrast to single-ring and PC events, it cannot be defined using one particular ring; the direction must be defined in an inclusive way. The vertex should first be determined using the standard method, then vectors from the vertex to individual hits in the photomultiplier tubes (PMTs) can be drawn. One way to define

	$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_s$	$\nu_\mu \to \nu_e$
$\rho_\mu^{sub}(53^o)$	$0.67 \pm 0.08^*$	$0.68 \pm 0.08^*$	$0.38 \pm 0.15^*$
$\rho_e^{sub}(53^o)$	Consistent at $2\sigma^*$	Consistent at $2\sigma^*$	$0.77 \pm 0.12^*$
$\rho_\mu^{multi}(78^o)$	0.52 ± 0.07	0.52 ± 0.07	0.24 ± 0.11
$\rho_e^{multi}(78^o)$	Consistent at 1σ	Consistent at 1σ	1.10 ± 0.08

Table 2: Values of $P_{\mu\mu}$ extracted from data on up-down ratios, assuming perfect angular correlation. ρ_μ includes both 1-ring μ-like and PC events. * Only statistical uncertainties are included in the sub-GeV case.

the direction of the event is the sum of all the vectors weighted by the corrected number of photo-electrons in the PMTs [8]. An equivalent way is to use the analog of the thrust variable in the QCD jet studies at e^+e^- colliders,

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}, \tag{5}$$

where the maximum is obtained by varying a vector with a unit length $\vec{n}$. The $\vec{n}$ which maximizes the thrust is the direction of a jet. At water Cerenkov detectors, the momentum vector, $\vec{p}_i$, can be taken as the vector to each PMT weighted by the corrected number of photo-electrons in the PMT. This value is approximate, as it ignores the dependence of photo-electron production on particle type [8]. The advantage of using the thrust variable is that one can study the thrust distribution to see if Monte Carlo calculations give a reasonable agreement with the data. Whatever definition of the direction of the event is employed, a detector simulation is necessary to study the correlation between the direction of the event and the original neutrino direction.

3 Multi-GeV Data

We propose an analysis of the zenith angle dependence in inclusive, multi-GeV, FC multi-ring events. According to the Monte Carlo study by the Super-Kamiokande Collaboration [2] summarized in Table 1, the FC multi-ring events are dominated by CC events. Since the multi-ring event sample is richer in multi-pion production and hence to higher energy neutrinos than the single ring event sample, the angular resolution is expected to be good. We actually do not know the breakdown of the FC multi-GeV multi-ring event sample into quasi-elastic (QE), single pion, and multi-pion production; the corresponding breakdown in the sub-GeV sample for Kamiokande experiment by Kajita [7] shows that the QE contribution is small (less than 5.9% with ν_e CC, ν_μ CC and NC combined), and the rest is roughly equally divided between single pion and multi-pion production.

In the multi-GeV sample, the multi-pion production is expected to be more important, and can roughly be approximated by the Deep Inelastic Scattering (DIS) processes, even though the energy of the neutrino is still relatively low. For the DIS processes, the correlation between the neutrino direction and the momentum of the hadronic system and the charged lepton can be studied, and is of course perfect if one can observe all of the momenta. Even though one misses both particles below the Cerenkov threshold and neutrons, the correlation should be better than for QE events, where it is 15–20% (RMS) [2]. Therefore, we assume in this paper that the FC multi-GeV multi-ring events have reasonable angular resolution, at least as good as the QE events. We advocate evaluating $\rho_{MR}^{multi}(\phi)$ with a large half cone angle of $\phi = 78^o$, so that only about 20% of the events are not used.

Once a direction of the event is defined, as outlined in the previous section, we can study the zenith-angle dependence of the FC multi-GeV multi-ring events. Since more than half of the events are expected to be ν_μ CC events, the same anomaly seen in μ-like one-ring events must also appear in this zenith angle dependence. In a 25.5 kt-years data sample, 398 events were observed, which gives roughly 11% statistical uncertainty in the up-down ratio.

The up-down ratio is also useful to study the nature of the oscillation, to distinguish $\nu_\mu \to \nu_e$ oscillation from $\nu_\mu \to \nu_\tau$ oscillation. We denote the survival probability of ν_μ as $P_{\mu\mu}$ as in the previous section. In the case of $\nu_\mu \to \nu_\tau$ oscillation, the rate for upward going ν_μ CC events is suppressed by the factor $P_{\mu\mu}$, while ν_e CC and NC event rates are unchanged. The resulting up-down ratio can be calculated using Eq. (2) and Table 1,

$$\rho_{MR}^{(\tau)multi} = 0.30 + 0.55 P_{\mu\mu} + 0.15. \tag{6}$$

For $\nu_\mu \to \nu_s$ oscillation, Eq. (3) gives

$$\rho_{MR}^{(s)multi} = 0.30 + 0.55 P_{\mu\mu} + 0.15 \frac{1 + r P_{\mu\mu}}{1 + r}. \tag{7}$$

Here, the ν_μ to ν_e flux ratio is roughly $r \approx 3$, suitably averaged over a range of energies and zenith angles, which can be studied in detail with their Monte Carlo analysis. Finally, the case of $\nu_\mu \to \nu_e$ oscillation is more complicated. The up-down ratio is

$$\rho_{MR}^{(e)multi} = 0.30(r - (r-1)P_{\mu\mu}) + 0.55\left(\frac{1}{r} + \frac{(r-1)}{r} P_{\mu\mu}\right) + 0.15 \tag{8}$$

from Eq. (4).

One important question is the theoretical uncertainty in the composition of the FC multi-GeV multi-ring events. The thesis by Shunsuke Kasuga [8] varied the CC and NC cross sections for sub-GeV data sample very conservatively by ±30% and ±50%, respectively. We take the same variation and determine the range allowed for the up-down ratio as a function of $P_{\mu\mu}$.

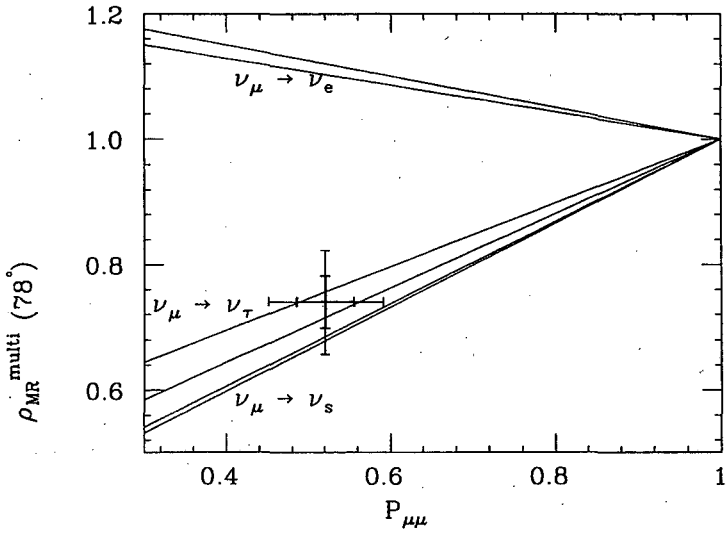

Figure 1: Up-down ratios in the FC multi-GeV multi-ring events for three oscillation scenarios. The CC and NC cross sections are varied by ±30% and ±50%, respectively, to give bands for each cases. The data point with large error bars correctly reflects the observed up-down ratio in multi-GeV μ-like events and its error in the horizontal direction, while the vertical position is yet to be measured. The large vertical error bar is the expected statistical uncertainty using 414 days of data. The smaller error bars correspond to four times more data – about 5 years.

Figure 1 shows the up-down ratios predicted for the three oscillation scenarios as a function of the ν_μ survival probability $P_{\mu\mu}$. An important point is that the up-down ratio is quite insensitive to the theoretical uncertainty in the cross sections. Another point is that three scenarios are relatively well separated, even though ν_τ and ν_s are somewhat close because of the small NC fraction. The current up-down ratio in the multi-GeV μ-like events determine $P_{\mu\mu}$ with an accuracy shown by the large error bar. The up-down ratio in the FC multi-GeV multi-ring events is not reported; we simply took a number with an anticipated statistical error. It is clear that the current data sample can distinguish the ν_e case and the other two. The measurement of the up-down ratio in this data sample will provide an independent consistency check of the observed anomaly, without relying on any particle identification.

4 Sub-GeV Data

The sub-GeV multi-ring data is potentially even more interesting than the multi-GeV data because it is rich in neutral current (NC) events, with a fraction f_{NC} of about a third. Therefore, this data sample has considerable power to discriminate between $\nu_\mu \to \nu_s$

oscillations and $\nu_\mu \to \nu_\tau$ oscillations.

The angular resolution is expected to be poorer than for the multi-GeV data. However, judging from a Monte Carlo calculation of the zenith-angle distribution of the one-ring μ-like events with neutrino oscillations [9], the zenith angular dependence is not completely washed out; rather it is diluted only by $D \approx 0.4$. The Super-Kamiokande Collaboration quotes a mean angular correlation in one-ring events to be 54% for muons and 62% for electrons [1]. Therefore, it appears that the zenith-angle dependence or, in particular, the up-down ratio can be studied even with the sub-GeV data sample. To be conservative, we study $\rho^{sub}_{MR}(\phi)$ with $\phi = 53^o$, ie. we use only the up-most bin ($\cos\Theta < -0.6$) and the down-most bin ($\cos\Theta > 0.6$) of the data. In this case, good angular resolution is not needed: $\Delta(\cos\Theta) \lesssim 2/5$, or $\Delta\Theta \lesssim 53°$ is sufficient, and is a reasonable expectation.

The most interesting component of the sub-GeV, multi-ring events is the NC, which is made of single π^0 production and multi-pion production with almost an equal amount according to Kajita's table [7]. The angular dependence in the single π^0 production was studied by Diwan and Goldhaber [4], and is quite good. They proposed to study this mode exclusively by enhancing the angular resolution with a kinematical cut whose efficiency is lower than 30%. We, on the other hand, are interested in studying the multi-ring sample inclusively to collect maximum statistics. Even without cuts, the contamination from the wrong bins is not large. Furthermore, the multi-GeV μ-like data suggests that the zenith-angle distribution is more-or-less flat for the first two bins and the last two bins. This also helps us to reduce the problem of poor angular resolution. Finally, multi-pion production in the NC data is expected to show a good angular resolution, much better than the one-ring events. The NC multi-pion production in the sub-GeV category is coming from higher energy neutrinos than the single-ring events because (1) the loss of the lepton energy makes the NC events appear less energetic than they actually are, and (2) the cross section rises as a function of energy unlike the QE and single-pion processes. We studied the angular correlation between the neutrino momentum and the momentum of the hadronic system numerically, and found indeed that the correlation is excellent (Fig. 2). In reality, one cannot measure the total momentum of the hadronic system, because neutrons are not seen, and protons have a high energy threshold for Cerenkov radiation. The true resolution needs to be studied with a full detector simulation. Still, it appears reasonable to assume that the angular resolution is sufficient for our analysis.

Following the same analysis as for the multi-GeV data set, we show the expected behavior of the up-down ratio ρ^{sub}_{MR} as a function of the ν_μ survival probability $P_{\mu\mu}$ for three oscillation scenarios. By varying the CC and NC cross sections by $\pm 30\%$ and $\pm 50\%$, respectively, the three scenarios give bands shown in the Figure 3. Just like for the multi-GeV sample, the ratios are quite insensitive to a large variation of the cross sections. The important point is the ν_τ and ν_s scenarios are well separated. This figure is drawn with a dilution factor $D = 1/3$ in the up-down ratio, conservatively allowing for a poor angular correlation. In this plot, we assumed that all of the events had the same dilution, which is probably a too pessimistic assumption; the multi-ring NC events must have better angular correlations than the QE events as discussed above.

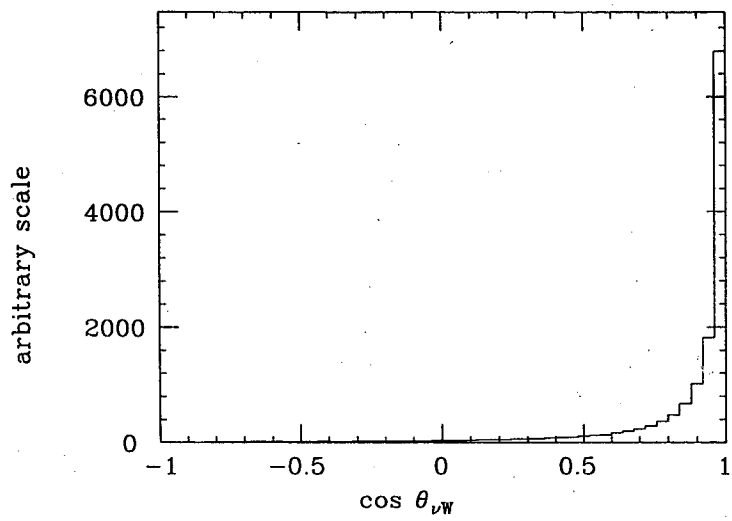

Figure 2: The angular correlation between the momentum of the neutrino and the hadronic system W in DIS NC events. The neutrino energy spectrum is taken from the calculation of Honda *et al* [6].

The published data set has 696 sub-GeV multi-ring events. Because we conservatively use only the up-most and down-most bins, the expected current statistical error is about 12%. It is clear that oscillations to ν_e and to ν_τ can be clearly separated. In a few years, the ν_τ and ν_s scenarios will be separated as well.

5 Conclusions

We have proposed a new test for atmospheric neutrino oscillations using currently available data: the up-down ratio of FC, multi-ring, inclusive events, ρ_{MR}. This method has good statistics and does not require particle identification. We anticipate that, with 414 days of data, two signals for neutrino oscillation could be obtained, one at the 3σ level. This would provide an important, independent test of atmospheric neutrino oscillations. These measurements, one with sub-GeV data and the other with multi-GeV data, could also confirm that ν_μ oscillate to ν_τ or ν_s, and not to ν_e. We believe that ρ_{MR}, like $\rho_{e,\mu}$ are currently statistics limited, so that the significance of these measurements will improve with time. Combining ρ_{MR}^{sub} and ρ_{MR}^{multi} results could allow a 2σ separation of ν_τ and ν_s modes with 5 years of data. With 5 years data it is likely that Δm^2 can be reliably extracted from the zenith angle dependence of the 1-ring e-like, 1-ring μ-like and PC events. It may then be possible to increase the significance of the sub-GeV, multi-ring analysis by including data from all zenith angles. We believe that our sub-GeV analysis has been conservative: we have included a large dilution factor for angular correlations, we have taken very large uncertainties in the neutrino cross sections, and we have not

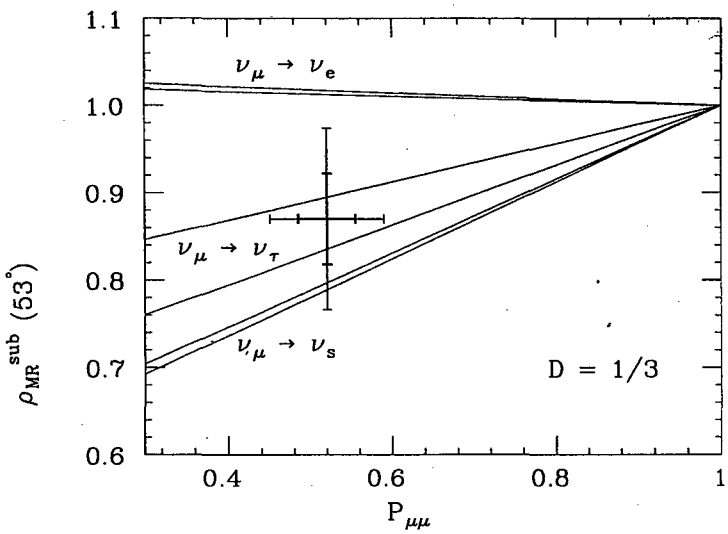

Figure 3: Up-down ratios in the FC sub-GeV multi-ring events for three oscillation scenarios. The CC and NC cross sections are varied by ±30% and ±50%, respectively, to give bands for each cases. The data point with large error bars correctly reflects the observed up-down ratio in multi-GeV μ-like events and its error in the horizontal direction, while the vertical position is yet to be measured. The large vertical error bar is the expected statistical uncertainty using 414 days of data. The smaller error bars correspond to four times more data – about 5 years. Only the upmost ($\cos\Theta < -0.6$) and downmost ($\cos\Theta > 0.6$) bins out of 5 are used, and a dilution of the ratio is included by taking $D = 1/3$.

attempted to optimize the cone angle ϕ, so that it will be possible to improve the power of this technique.

Our analysis has largely been based on the assumption that the oscillations involve only two flavors of neutrinos. Ultimately, it will be important to perform a global analysis of the various up-down ratios using the predictions of (1) for general neutrino oscillations. The fit is overconstrained, as there are seven event classes: e-like 1-ring, μ-like 1-ring and multi-ring for the sub-GeV data; FC e-like 1-ring, μ-like 1-ring and multi-ring, as well as PC events, for the multi-GeV data. The averaged neutrino flux ratio, r, is close to 2 for the sub-GeV data, but for the multi-GeV data it is considerably higher, and depends on the cone angle ϕ. Hence, with several years of data, it will be possible to fit the seven up-down ratios to obtain values for the five oscillation probabilities $P_{ee}, P_{e\mu}, P_{\mu e}, P_{\mu\mu}$ and P_s.

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