VERY PRELIMINARY

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Evidence for Neutrino Oscillations in the Muon Sector

The Super-Kamiokande Collaboration

ABSTRACT

The new neutrino observatory, Super-Kamiokande, located in Western Japan has been collecting data since April 1996. Super-Kamiokande is a 50,000 m^3 water-Čerenkov detector. Contained neutrino interaction data with energy between 50 MeV and 10 GeV in deposited energy has been analyzed from 300 days of live time. We report upon the examination of the identified muon and electron events in terms of the hypothesis of neutrinos of atmospheric origin undergoing flavor oscillations. We find that no-oscillations is rejected at the 99% level. While we have not excluded many of the huge number of possible scenarios, acceptable fits between the data and simulations are found for muon neutrinos oscillating to either tau neutrinos or another sterile species, and no evidence for electron neutrino oscillations in our sensitive region in mass squared differences ($\delta m^2 = 0.001 - 0.1\ eV^2$). We find that the muon neutrino mixing must be nearly maximal, with $\delta m^2 = 0.005\ \ -0.004\ \ +0.005\ eV^2$. This region has been indicated previously as a possible resolution to the "atmospheric neutrino anomaly". Here we present the first evidence that the effect depends upon distance (angle of arrival) and energy, in a manner consistent with neutrino oscillations. Note that with our as yet limited statistics we cannot claim certain discovery of neutrino oscillations, but this conclusion is certainly the most favored interpretation of our present data set.

1 Introduction

For many years now we have known that there is a discrepancy between the predicted and observed ratio of muon neutrinos to electron neutrinos of atmospheric origin in the energy range of around 1 GeV[1, 2, 3, 4]. This anomaly is seen in not only different channels in the water Cherenkov experiments (identified muon and electron event topologies, and also in the fraction of events containing muon decays), but also (with limited statistics) in the Soudan detector[3], which employs a different target and has completely different systematics. Moreover, with increasing detector size the discrepancy between data and predictions employing standard physics has become more inescapable. Many suggestions of systematic and calculational problems have been put forward, have been investigated, but none have provided an escape[5]. Since the first observations of the anomaly we have been aware of the possible interpretation as neutrino oscillations. Yet, because of limited statistics we have not had the ability to find compelling evidence for oscillations in terms of variation with distance and energy. We now have some evidence in hand.

In the standard form of vacuum neutrino oscillations, the probability of neutrino oscillation from one flavor to another varies with $sin^2(\delta m^2 L/4E)$, where the δm^2 is the mass difference between two mass eigenstates, L is the flight path, and E the neutrino energy. Many clever schemes for neutrino mixing have been put forward to interpret the three present neutrino anomalies which are in solar neutrinos, the presently considered atmospheric anomaly and the more recent suggestion of oscillations from the LSND experiment[7]. We cannot review them all here[6]. We focus upon the possibility of simple hierarchical neutrino oscillations[8] for the present, since as we will show, they provide an adequate explanation of what we do observe. However, we caution the reader that other solutions assuredly have not been ruled out (though some are certainly disfavored).

In the past the data has indicated a simple deficit in the muon/electron neutrino ratio (quoted most often in terms of the ratio R of the muon to electron neutrino fluxes observed, divided by the predicted ratio), without our being able to know whether the muons were disappearing, the electrons appearing, or muon neutrinos being transmuted to electron neutrinos. We have not seen previously, due to limited statistics, the expected variation due to oscillations in energy and angle. Herein we present the first evidence in that direction.

2 The Super-Kamiokande Detector

Super-Kamiokande is a water-Čerenkov detector built to study a variety of physics topics, ranging from solar neutrino studies, to the search for nucleon decay, to neutrino astronomy. The exterior of Super-Kamiokande is a stainless steel tank 41 m tall and 39 m in diameter which holds $50,000\ m^3$ of ultra pure water. This volume is divided into two optically separate detectors, inner and outer. The inner detector contains $32,500\ m^3$ of water ($22,500\ m^3$ viewed by 11,146 photomultiplier tubes (PMTs) 50 cm in diameter, covering 40% of the area. The 1 pe timing resolution of these large PMTs is 2.8 ns. The outer detector forms a cylindrical shell surrounding the inner volume and is used to differentiate between events with entering, exiting, and contained particles. This 2.5 m thick veto shield is instrumented with 1,885 PMTs with accompanying waveshifter plates to increase the total light collection area. The outer PMTs are 20 cm in diameter and face towards the outer wall of the Super-Kamiokande tank. Both walls defining the outer detector are lined with a reflective material to enhance the overall light collection efficiency of the outer PMTs. The detector is located in a lead and zinc mine near Kamioka, Japan at a depth of 2800 mwe.

Since Super-Kamiokande is situated underneath a mountain, the rate of cosmic-ray muons triggering the detector is reduced to $\sim 2.2\ Hz$. The remainder of the $10 - 12\ Hz$ of triggers from Super-Kamiokande are low energy events. The current trigger threshold (defined as the energy where the trigger is 50% efficient) is $\sim 5.5\ MeV$. The majority of the low energy triggers are background for the solar neutrino analysis. The data with which we are concerned in this report is thus recorded with high efficiency.

Because of the high event rate, the significance of the measurements made by Super-Kamiokande will ultimately be limited by systematic uncertainties, not statistical errors. For this reason, two groups within the Super-Kamiokande collaboration each perform completely independent analyses. All data filtering, event reconstruction, and cut selections are done separately. The only overlap between the two groups is the use of the raw data and the data from various calibration sources. Moreover, the analysis groups have employed three distinct Monte Carlo simulations for the data presented below. The consistency between results gives us confidence of the lack of significant analysis error.

3 Data Reduction

****¿¿¿¿ Insert section here, with modest level of detail, and mainly refer to SK HE paper on 200 day contained data, PL (in preparation). Emphasize effiency of collection of events within the volume, lack of significant systematics, and high degree of identification of single ring events.

4 Preliminary Results

In Figure 1 we present the variation with energy of an up-to-down asymmetry for muon and electron events ($A = (D-U)/(U+D)$), separately. The use of this ratio has the virtue that many possible systematics factor out, leaving the physics variation to be exposed with good statistical weight. The data was selected to be between 200 MeV and 5 GeV in visible energy. Below this energy range the angle determination deteriorates, and above the muons are not likely to be contained.

In the presence of no oscillations this plot should show no variation beyond a few percent due to some asymmetry in the earth's magnetic field's effect on incoming cosmic rays[9]. One sees no discernable trend in the electron data, while the muon asymmetry is 0.17 ± 0.05. In Figure 2 we present a theoretical calculation of the asymmetry expected for muon neutrino oscillations with $\delta m^2 = 0.005\ eV^2$. The calculation is for charged current events alone and does not contain experimental details, and thus represents what one might expect froman ideal detector. [Here we should add or substitute an MC calculation of the asymm.]

This asymmetry data is suggestive, but not compelling statistically, as yet. We note that this is however, the first evidence that the anomaly is surely in the muon channel and not in the electron channel. Note also that the asymmetry in the data does not depend upon any calculated flux or flux ratio: it is an independent test of the two neutrino channels. And this test demonstrates variation in angle and energy, the hallmarks of oscillations. No Monte Carlo simulation is required to demonstrate that the suggestions considered to date for systematic means to explain away the anomaly are strongly rejected. We only require the simulation to interpret the results in terms of some particular oscillation parameters, as we discuss below.

In Figure 3 we present a plot of the electron and muon data as a function of $Log_{10}(L/E)$. The data spans roughly 5 orders of magnitude because we have ranges of a factor of 25 in energy, and 10^4 in distance from overhead to upcoming. Unfortunately the energy we record from Super-Kamiokande is not the true neutrino energy, and is rather widely distributed below the true neutrino energy (typically the visible energy is around 1/2 the neutrino energy)[1]e use estimators $E_{\nu_e} = E_{vis} + 487\ MeV$ and $E_{\nu_\mu} = 1.1 \times E_{vis} + 360\ MeV$. Moreover we do not reconstruct the neutrino angle very well (at best a few degrees, but often much worse). Also we cannot know the point of origin of the neutrino in the atmosphere. We have employed an approximation to the mean distance [9], and explored the effect of varying the effective production altitude. We conclude that the varying range, which is fractionally large for neutrinos straight downcoming, has little effect on the present analysis because, fortuitously, the neutrino oscillation length we find ($\sim 250\ km$ for neutrinos of about $1\ GeV$) is much longer than the distance from overhead. Our resolution in L/E is shown on a log scale in Figure 4, where one sees that the FWHM of the distribution is about 0.2.

In the presence of oscillations one would like to see a "chirped" like signal in the L/E plot, Figure 3. In practice we have not achieved sufficient resolution (nor at present is it clear that one could do so even in an ideal detector of atmospheric neutrinos) to see the oscillatory signature, but only a smooth decrease from the expected number at the left (small L/E) as one moves to large neutrino oscillation times (large L/E), to a reduced (oscillated) fraction. In the upper portion of Figure 3 we show the observed data, with simulated data overlayed (dashes), for no oscillations for electrons (a) and muons (b). The Monte Carlo sample is equivalent to about 7.75 years of data, and is normalized to the observed livetime in this figure. We observe that in the ratio of simulated to predicted data, shown below, the electrons (c) are prefectly consistent with predictions whilst the muons (d) are not.

In Figure 5, we show the results of a calculation which injects neutrino oscillations into the simulated data set and calculates the χ^2 difference between observed and oscillated simulation data. We have used Poisson statistics for

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calculating equivalent χ^2 values where the bin contents are small. We present here a test of the hypothesis of muon neutrinos oscillating into another unseen neutrino (which could be tau or a new sterile neutrino), with no effect occurring upon electron neutrinos. The dotted line shows the effect of normalizing the event totals to the muons in data and simulation, and testing the electron fit. This is equivalent to a test of R (the ratio of muon to electron neutrinos, observed to predicted) as we have presented previously, and shows a broad minimum in the region around 0.005 eV^2.

The dashed curve show the independent results of normalizing the muon flux whilst testing the χ^2 of muon data to oscillated simulated data. This test then is sensitive to the shape of the oscillation signal in L/E space, and again one sees a broad minimum. The same test with no-oscillations yields a $\chi^2/DOF = 146/10$, a very poor fit.

Finally in the solid curve we show the result of a fit in which we normalize the electron fluxes, and simply test the observed muon flux versus the oscillated muon simulation. The hypothesis thus tested is: given that the simulation describes the electron data adequately, what muon oscillation parameters would be needed to describe the observed data? We find an acceptable fit with maximal mixing and $\delta m^2 = 0.0048$, with the error best expressed as a multiplicative factor of 2.2. This value is gotten by fitting the curvature of the χ^2 near the minimum.

In Figure 6 one sees a plot of the χ^2/DOF of the muon neutrino oscillation hypothesis as we vary δm^2 and mixing angle, $sin^2(2\theta)$. One sees that the mixing angle must be close to maximal, with one sigma being at about $sin^2(2\theta) = 0.8$.

5 Conclusions

In summary we are not claiming as yet to have definitively observed neutrino oscillations while simultaneously rejecting all other explanantions. However, we now do have evidence which is prefectly compatible with oscillations while incompatible with no-oscillations at the 99% level. And the data we have in hand behaves correctly in terms of L/E variation to be neutrino oscillations (where previous tests were insensitive to this variation). In tests which will be presented elsewhere, we will show that the present data is incompatible with some neutrino oscillations schemes such as the maximal mixing scheme of Harrison, Perkins and Scott[10], and schemes which vary with $L \times E$ [11, 14]. Our present data leads us to $\delta m^2 \; = 0.005 \; + 0.005 \; - 0.004 \; eV^2$ with near maximal mixing for muon neutrinos oscillating to another unseen species. The result is potentially compatible with the models of Acker and Pakvasa[12], and Fogli, et al.[13]. [this needs tuningup... as we get time to fit the various models... in progress]

With the data presented herein representing 300 days of equivalent detector operations, or about one year of calendar time, we can expect that the statistical errors will be halved in a further three years. Further improvements in analysis, gotten though identifying better algorithms for determination of the unseen neutrino's L/E and perhaps better identification of event classifications may help.

Acknowledgements

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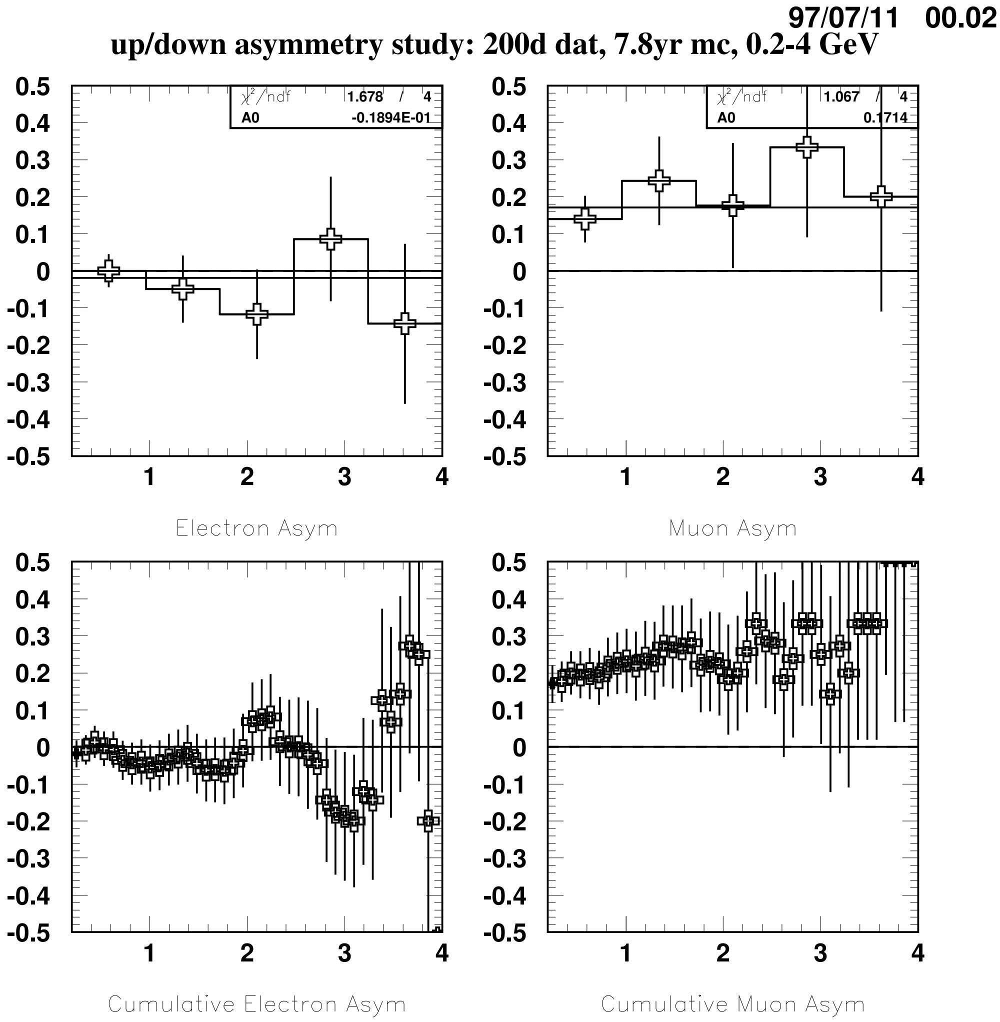

Figure 1: Up-to-down asymmetry for electron-like and muon-like events in Super-Kamiokande as a function of observed energy. Upper plots are with independent bins, lower show cumulative asymmetry.

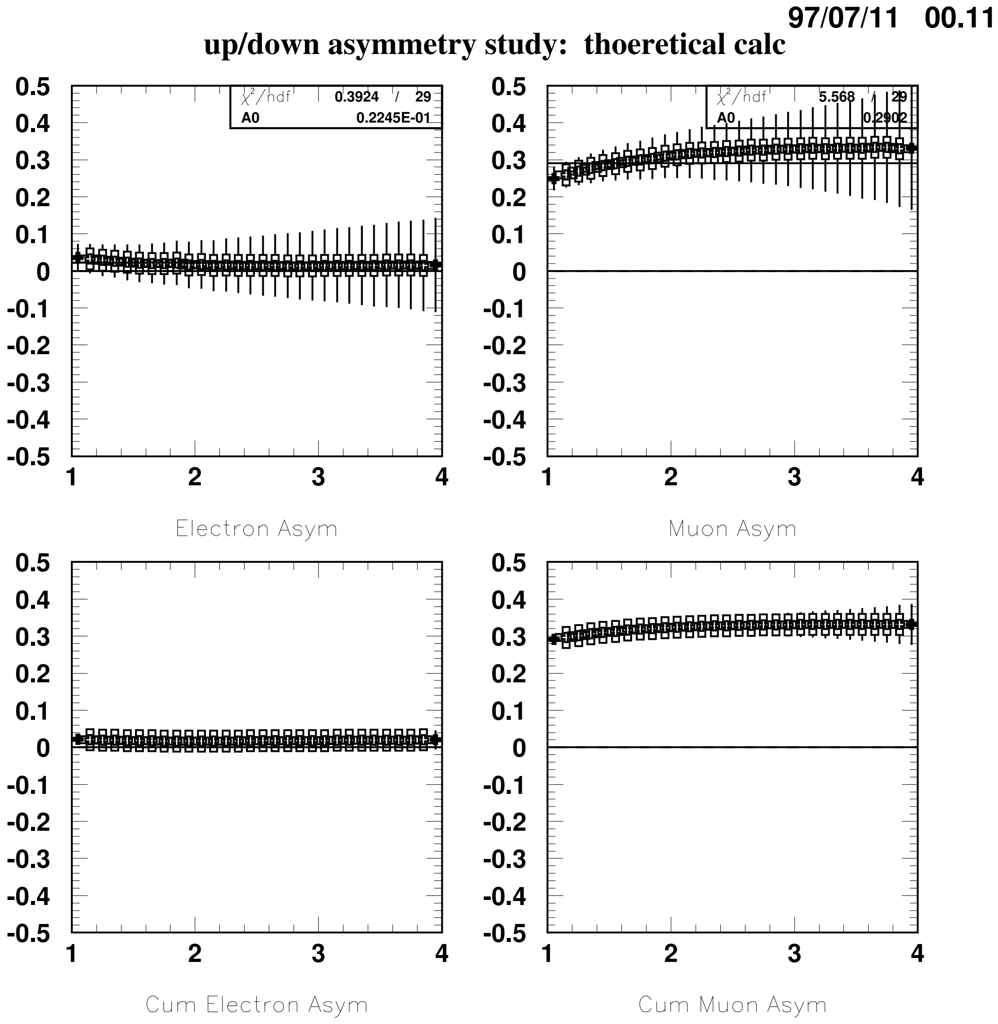

Figure 2: Up-to-down asymmetry for muon-like and electron-like events in Super-Kamiokande as a function of energy from a theoretical calculation with muon neutrino oscillations inserted with $\delta m^2 = 0.005\ eV^2$ and full mixing.

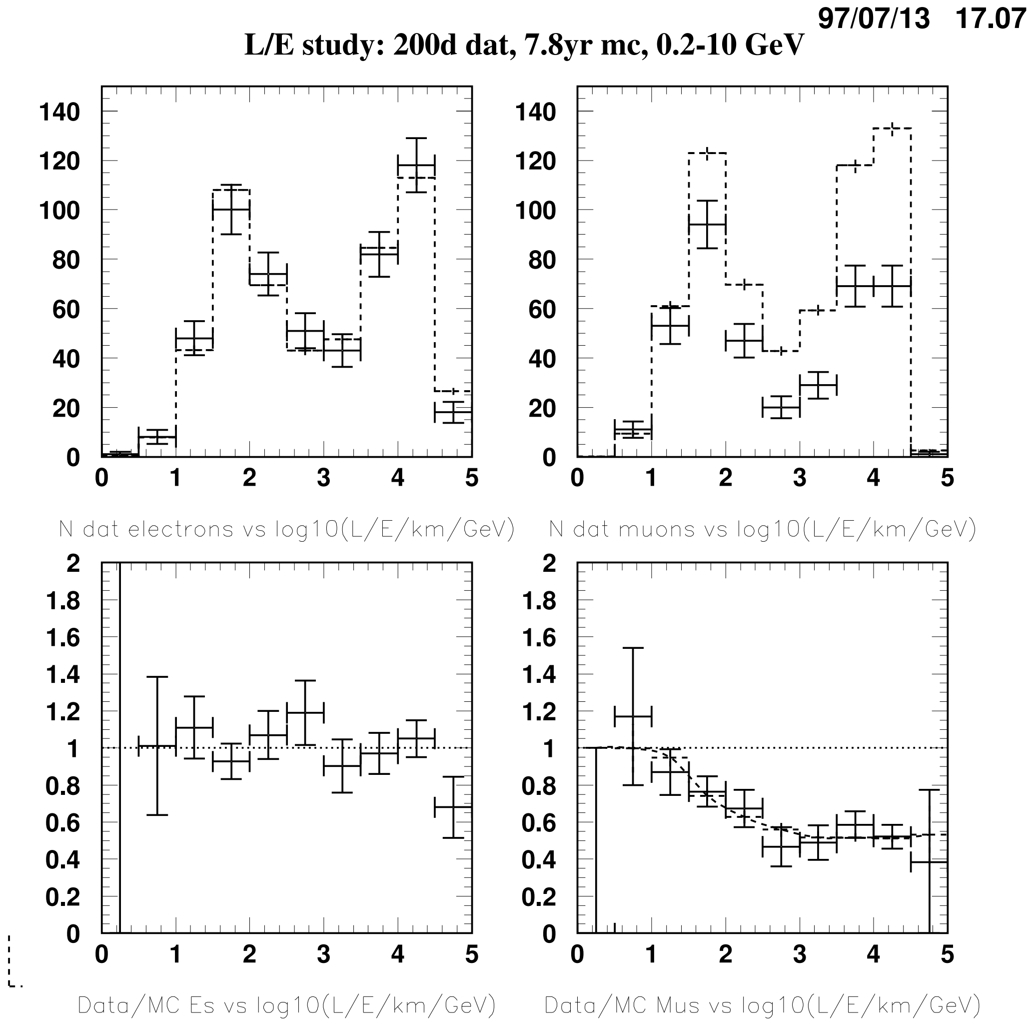

Figure 3: The distribution in observed events with visible energy between 200 MeV and 5 GeV in Super-Kamiokande in contained events from the first 300 days, plotted as a function of the neutrino flight distance divided by energy, L/E, on a logarithmic scale. The data is shown for electrons (a) and muons (b), with simulation events overlayed by a dashed line. The ratio of observed to predicted flux is presented in (c) and (d).

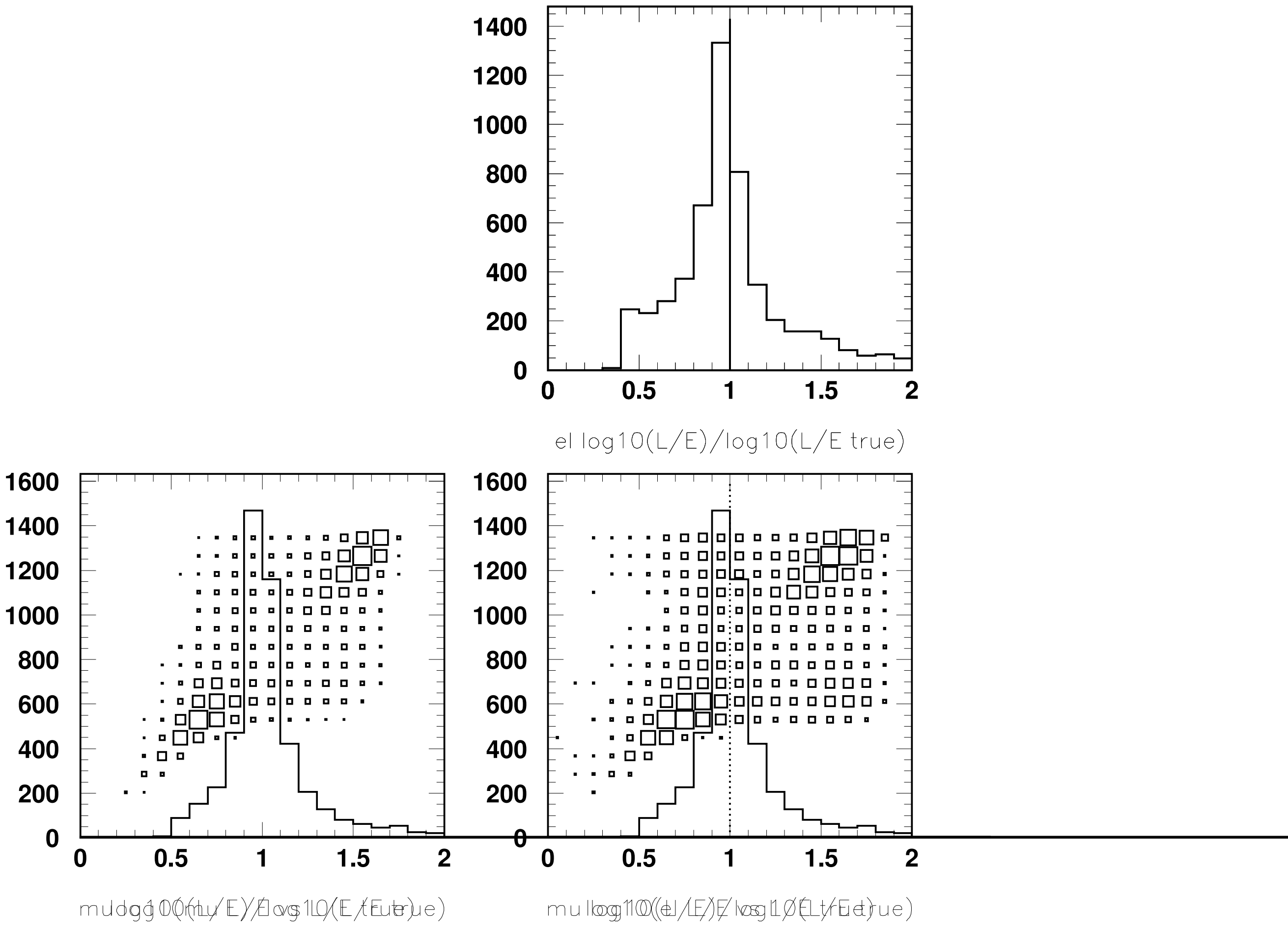

Figure 4: The resolution in L/E on a logarithmic scale, as calculated using simulated data for reconstructed and true input values of neutrino flight distance and energy.

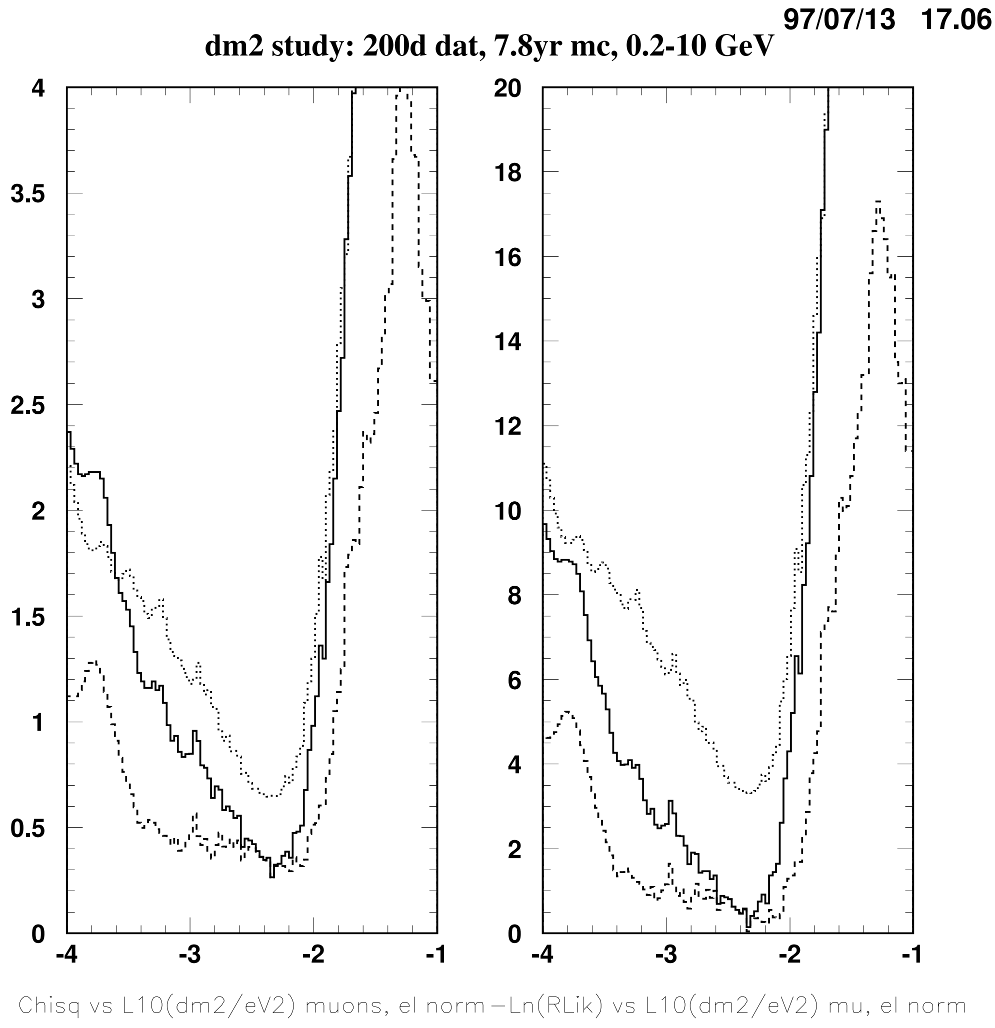

Figure 5: The values of equivalent χ^2 between observed and simulated data, with several hypotheses versus the trial value for muon neutrino oscillation with δm^2 as shown. The dashed curve shows the results for testing the electron distribution in L/E space,while normalizing the real and simulated muon data (R test). The dotted curve shows the results for testing the muon data alone, while normalizing the muon event totals (L/E shape test). Finally, the solid curve shows the result for normalizing the elctron total while testing the muons (shape and R test).

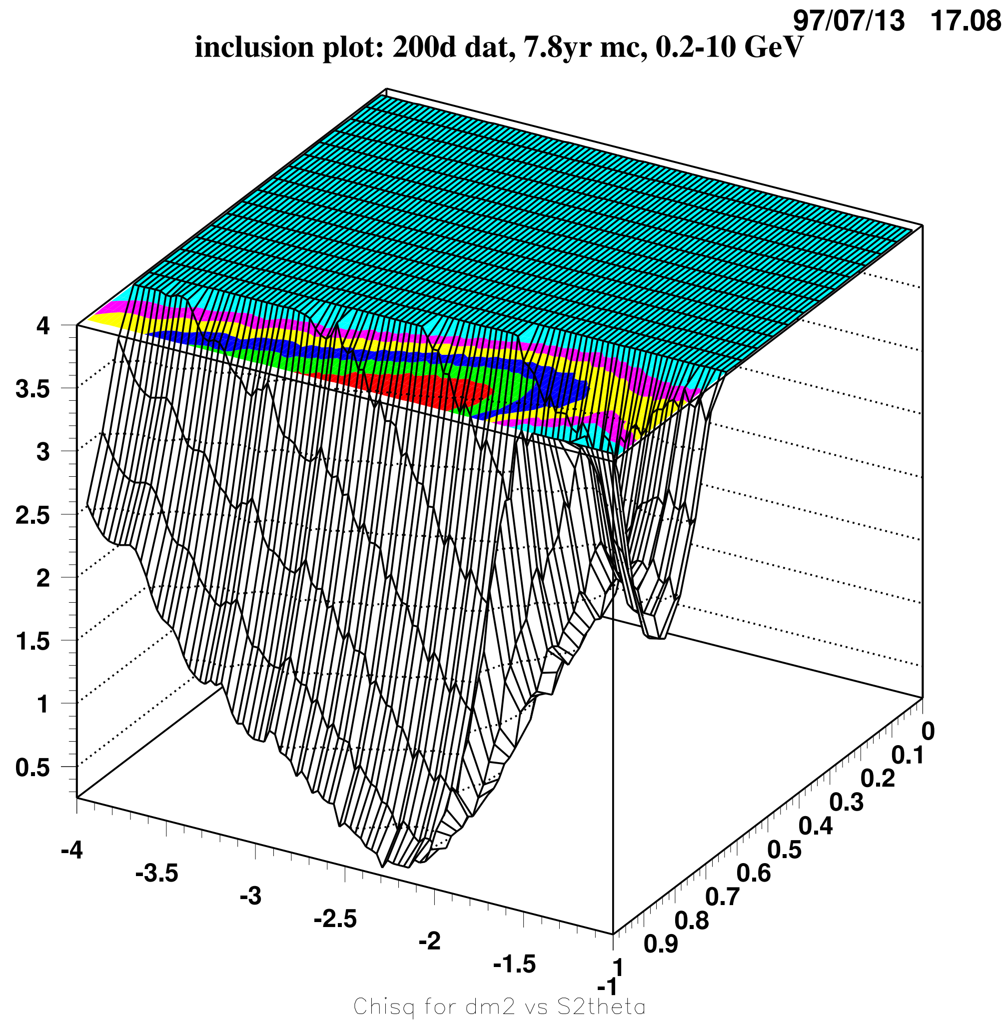

Figure 6: A plot showing the contours of acceptability of fits to the 300 day Super-Kamiokande contained event data under the hypothesis of muon neutrino vacuum oscillations to an unsee neutrino.