Analysing the Fast Oscillations of Atmospheric Neutrinos at Super-Kamiokande

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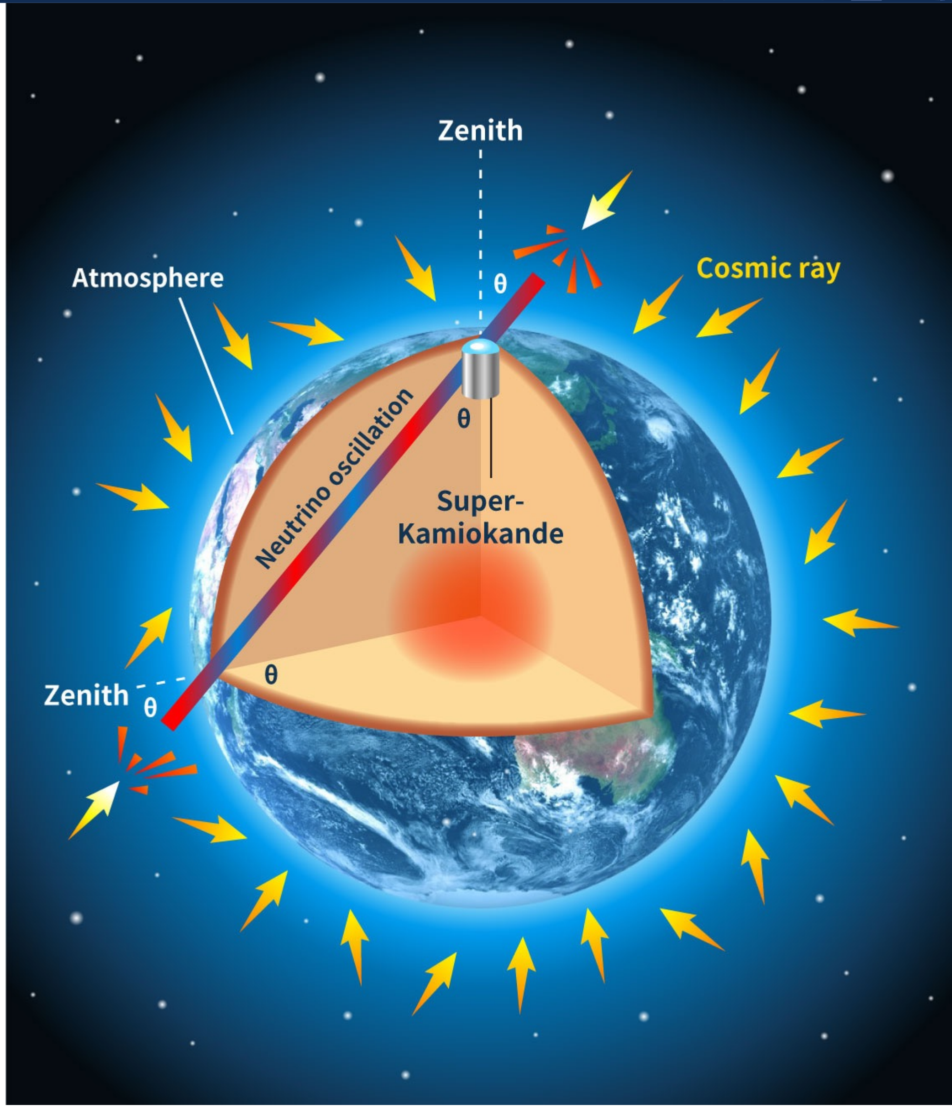
Introduction

- The Super-Kamiokande detector is the largest, and arguably the most successful, neutrino detection experiment of its kind currently in operation.

- Super-K can detect neutrinos from many sources, but the focus of this presentation will be on <u>atmospheric neutrinos</u>, specifically on <u>Sub-GeV</u> neutrinos which travel <u>Upwards</u> through the Earth.

- These types of neutrinos undergo <u>neutrino oscillations</u> at a far higher rate, compared to higher energy atmospherics.

- This feature, referred to <u>"Fast Oscillations"</u>, means that for MC simulations to accurately model the observed data, we must either produce a sufficiently large amount of MC (impractical), or introduce techniques which average the oscillation probabilities for these types of neutrinos.



https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/research/

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Atmospheric Neutrinos

- **Primary cosmic rays (high energy protons) interact with the molecules Earth's upper atmosphere to produce a cascade of secondary particles, mainly $\pi^{\pm}$, n and $\mu^{\pm}$.**

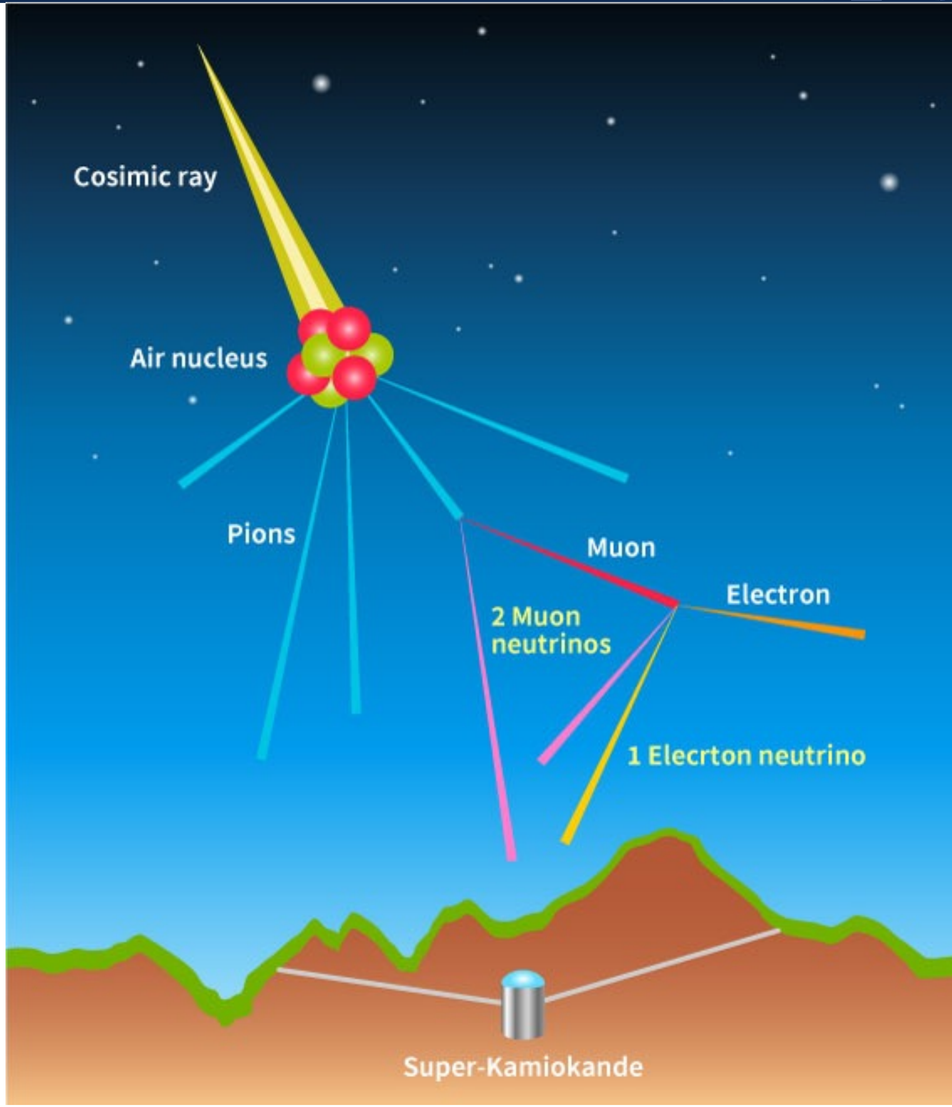
- **The majority of these secondary cosmic rays are charged pions, which then decay into μ^{-} (μ^{+}) and $\bar{\nu}_{\mu}$ (ν_{μ}) in the following way**

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \quad \& \quad \pi^{-} \rightarrow \mu^{+} + \nu_{\mu}$$

- **These $\mu^{\pm}$ can then undergo additional decays**

$$\mu^{-} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu} \quad \& \quad \mu^{+} \rightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$

- **The neutrinos produced from these charged pion, and subsequent muon decays are known as atmospheric neutrinos.**



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Neutrino Oscillations

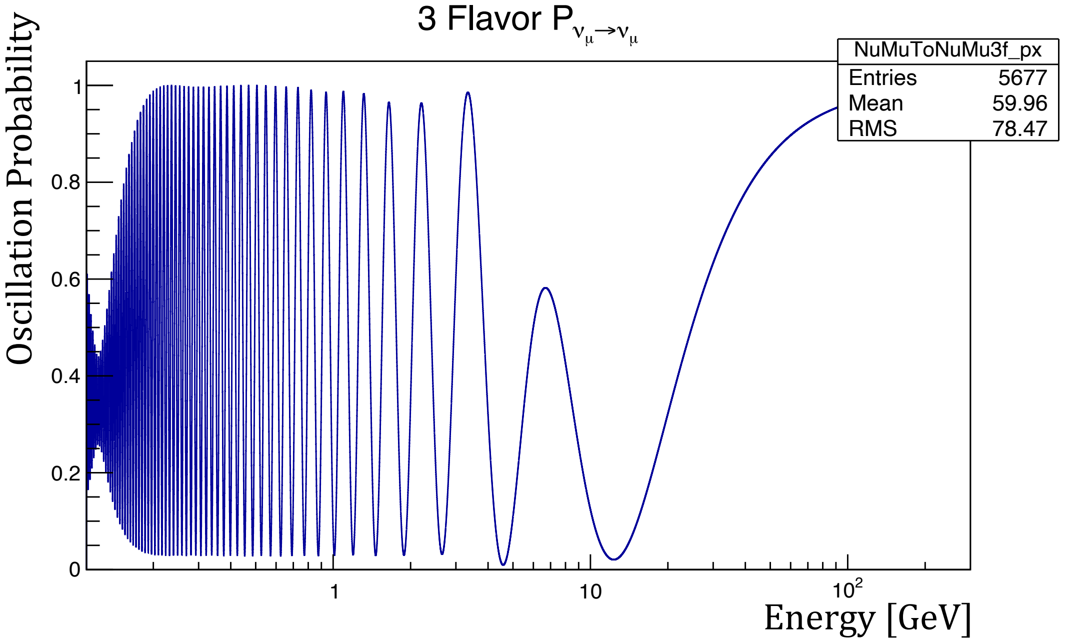
- As they propagate, these atmospheric neutrinos undergo neutrino oscillations, governed by the following formula

$$P(\nu_\alpha \rightarrow \nu_\beta) = \begin{cases} 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right), & \alpha = \beta \\ \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right), & \alpha \neq \beta \end{cases}$$

- Which is the two-flavour approximation for oscillations in a vacuum, where the top is the survival probability where no oscillation occurs
- The key point to note is the dependence on L / E, which gives rise to neutrino oscillations.
- Matter effects complicate things, but the L / E dependence is maintained
- In natural units, the argument of the $\sin^2$ function is $\frac{\Delta m^2 L}{4E_\nu}$ so the length of one complete oscillation is

$$L_{osc} = 4\pi E_\nu / \Delta m^2$$

See Luke Pickering's talk for more detail



Super-Kamiokande

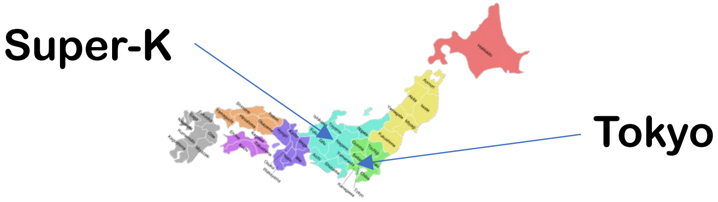
Super-K is currently the world's largest water Cherenkov detector, with a 41.4 m height and 39.3 m diameter total volume of 50 kton, and a 22.5 kton fiducial volume!

Consists of two optically separated regions;

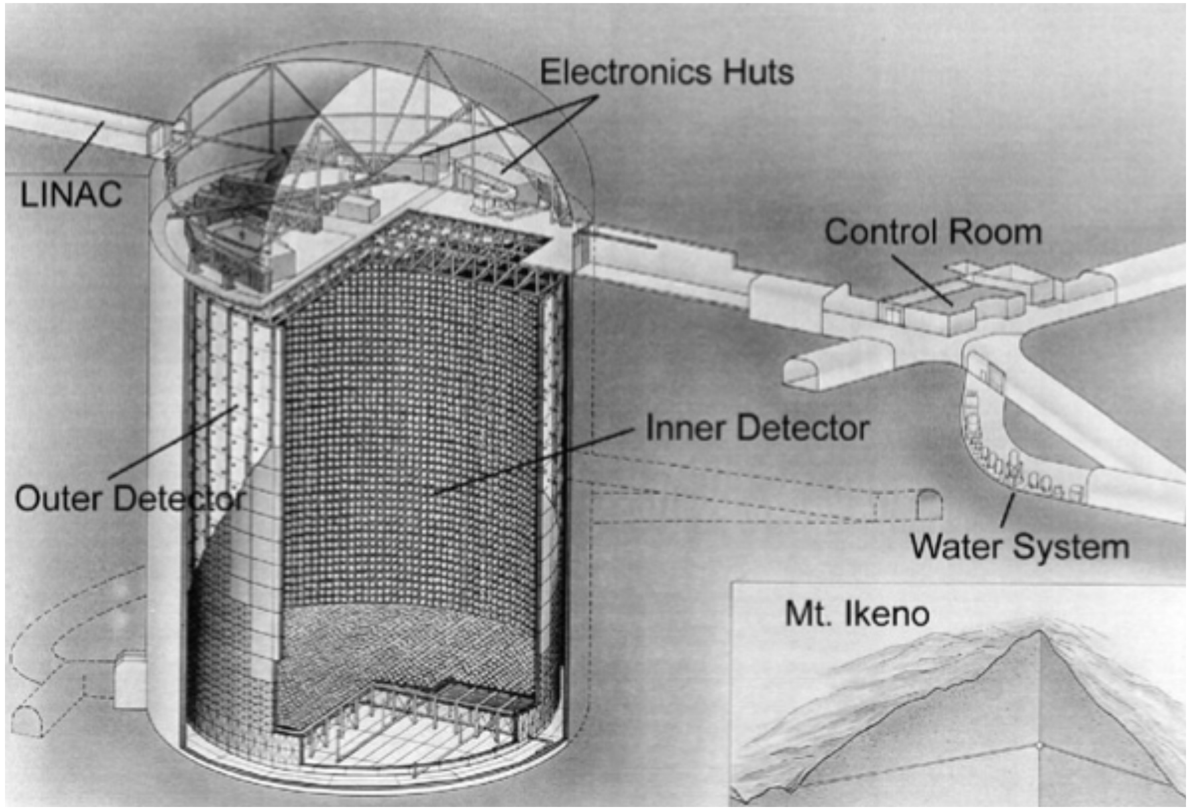
- Inner Detector (ID) which records the information used in event reconstruction. It contains 11,129 x 50cm PMTs
- Outer Detector (OD) which acts as a cosmic ray veto and contains 1,885 x 20cm PMTs inside 60x60 cm WLS plates

Filled with Ultrapure Water from 1996–2020 (SK-I – SK-V). Doped with $Gd_2(SO_4)_3$ from 2020–Present to improve neutron tagging efficiency and reduce background for other Physics Analyses.

This began with the SK-VI run period (2020 – 2022) with 0.011% Gd, and continued with SK-VII (2022 – Present) with 0.03% Gd.



Located 1000 m underneath Mt Ikeno in the Mozumi mine, near Kamioka, Japan.

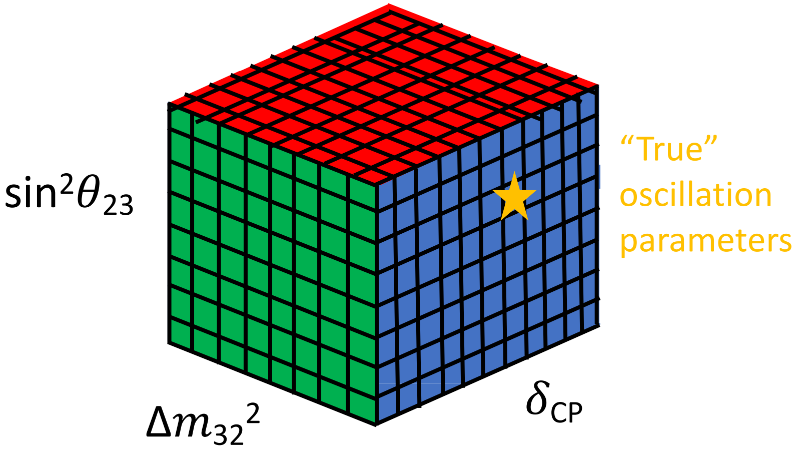


Atmospheric Oscillation Analysis Workflow

- **The Super-K Oscillation Analysis (OA)** aims to compare the binned neutrino event rates between data and the MC for different oscillation models.

Process data and produce MC using Geant3 or Geant4 based software → Assign types & bins to data and MC events → Calculate systematic effects → Apply oscillations to MC <u>This is where the "Fast Oscillations" are dealt with</u> → Calculate χ^2

- A particular oscillation model specifies a value of each of the oscillation parameters and the MC is then oscillated according to that model. A set of oscillation models forming a grid is chosen and this analysis performs a search over the lattice for the best agreement with data.



- Oscillation grids:
  - 6-dimension oscillation parameter space;
  - $\Delta m_{21}{}^2 \times \Delta m_{32}{}^2 \times \sin^2\theta_{12} \times \sin^2\theta_{13} \times \sin^2\theta_{23} \times \delta_{CP}$

$$\chi^2_{tot} = \sum_n \left[E_n - \underset{\uparrow}{O_n} + 0_n ln\frac{0_n}{E_n}\right] + \boxed{\sum_{kj}\epsilon_k\rho_{kj}^{-1}\epsilon_j}$$

Observed events

Systematic parameter correlations

Where $\underset{\uparrow}{E_n} = E_n^0(1 + \boxed{\sum_i^K f_n^i\epsilon_i)}$

Expected events

Fractional change caused by systematic parameter variations

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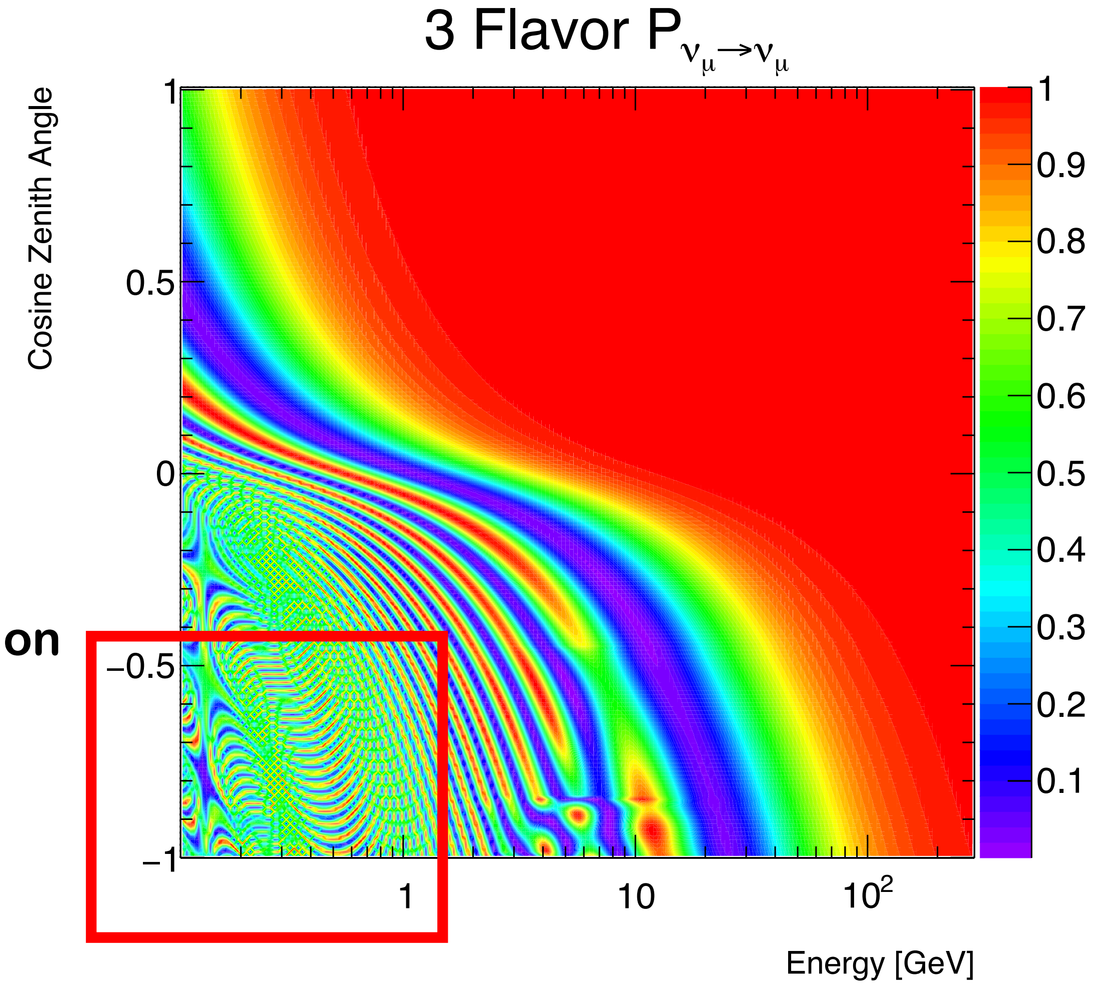
“Fast” Neutrino Oscillations

- **The exact oscillation probability calculation is calculated based on “Matter effects on three-neutrino oscillations” [Phys. Rev. D 22, 2718] and produces the oscillogram for ν_μ survival.**

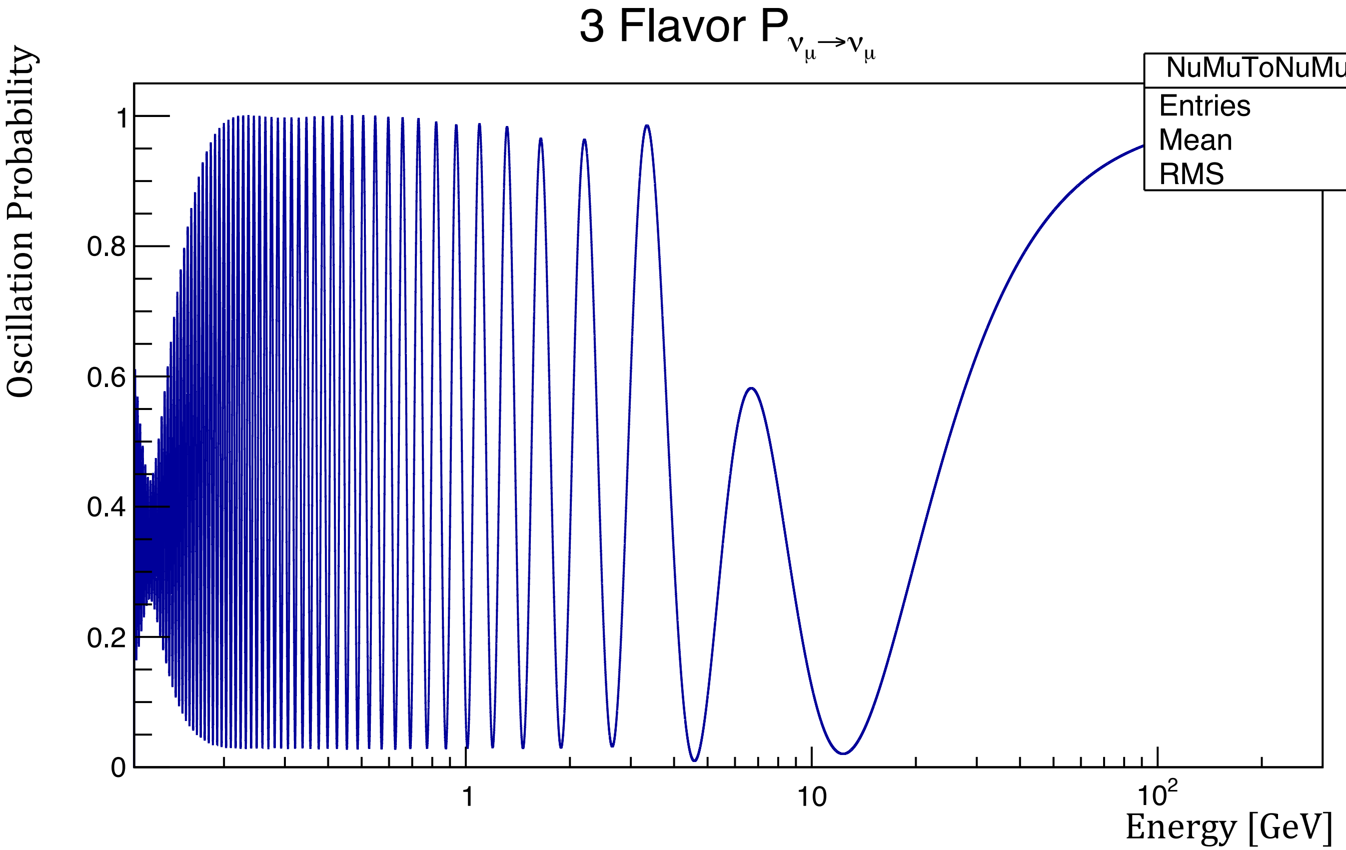
SubGeV Upward going region



“Fast” Neutrino Oscillations

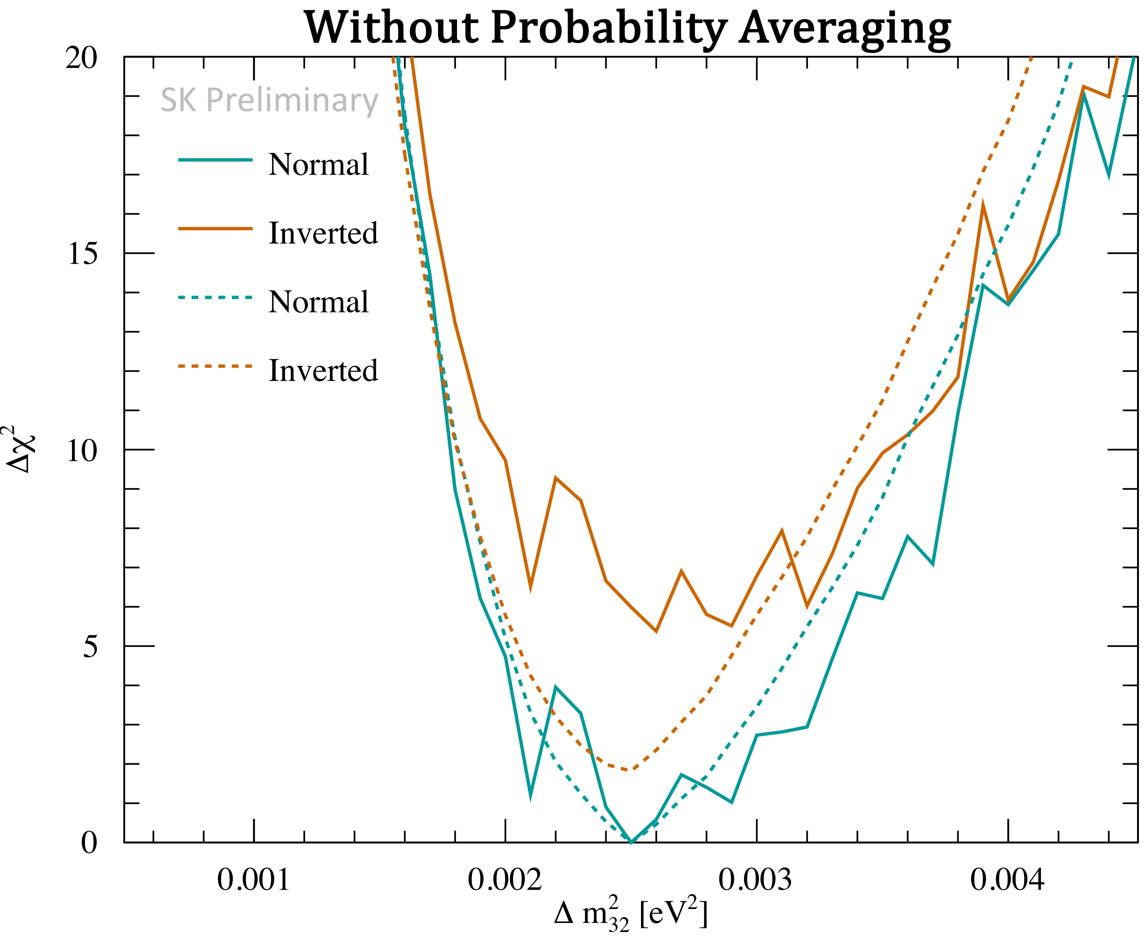
- **Taking a 1-D projection** of energy for fixed Cos(Zenith) = -0.5 gives the plot below

- The OA essentially samples from this distribution at energies specified by the MC, however this distribution is just a single sampling of nature's true distribution so a non-infinite MC will never sample perfectly, which is exacerbated in the “Fast Oscillation” region



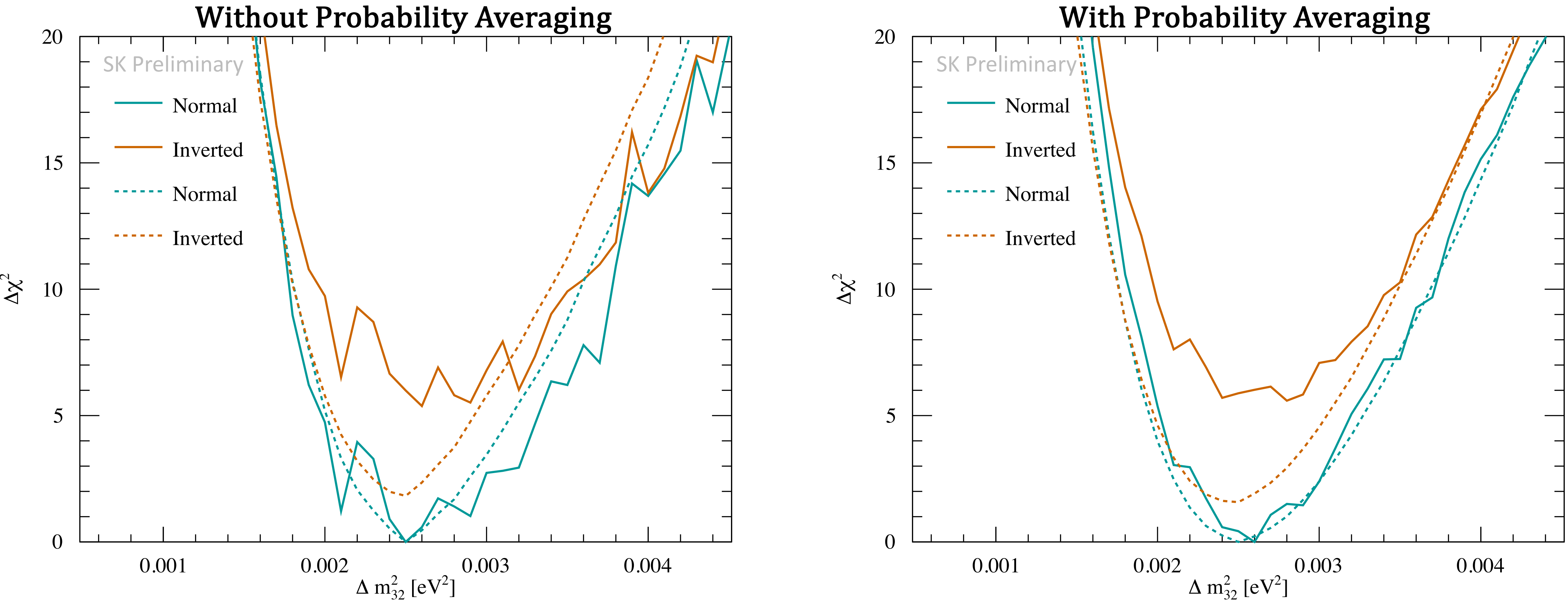
Current Status

- **Solid lines are mock data fits and dashed lines are sensitivity (Asimov) fits where MC is fitted to MC where the normal ordering is assumed true, and the "true" value of Δm^2_{32} is set to 0.0025 eV^2. This is for SK4 only & includes all systematic errors.**



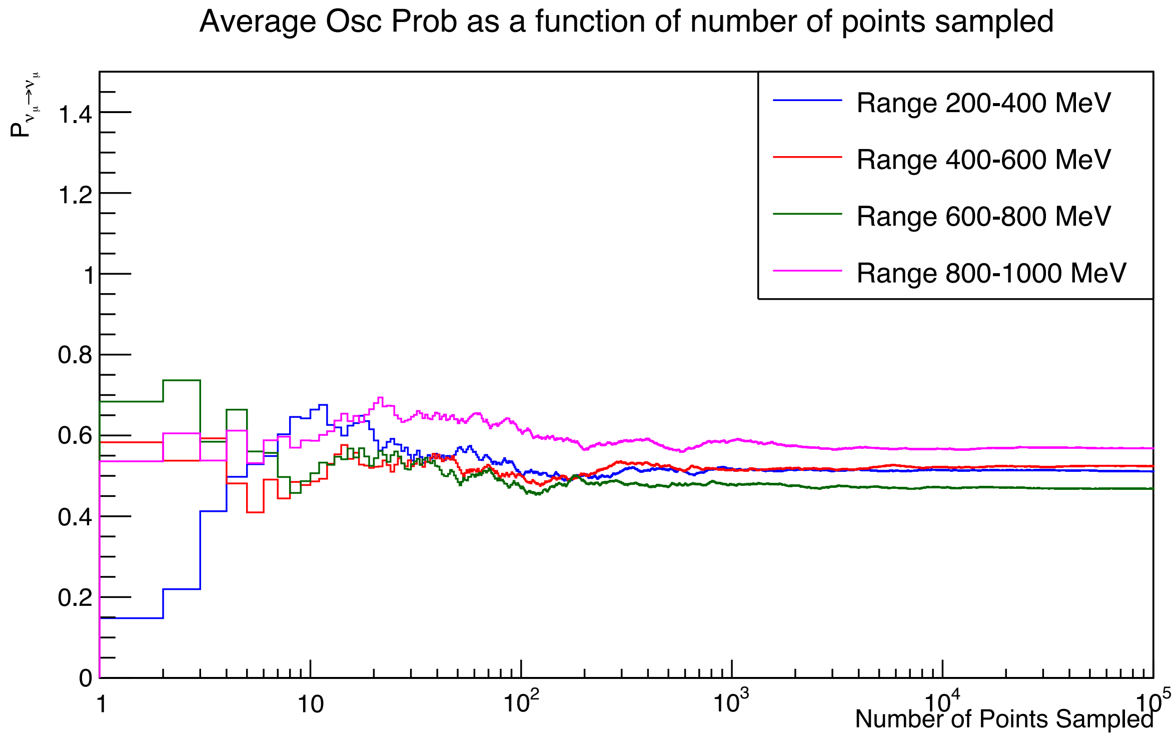
Current Status

- **Solid lines are mock data fits and dashed lines are sensitivity (Asimov) fits where MC is fitted to MC where the normal ordering is assumed true. This is for SK4 only & includes all systematic errors. Details on the current averaging treatment in backup.**



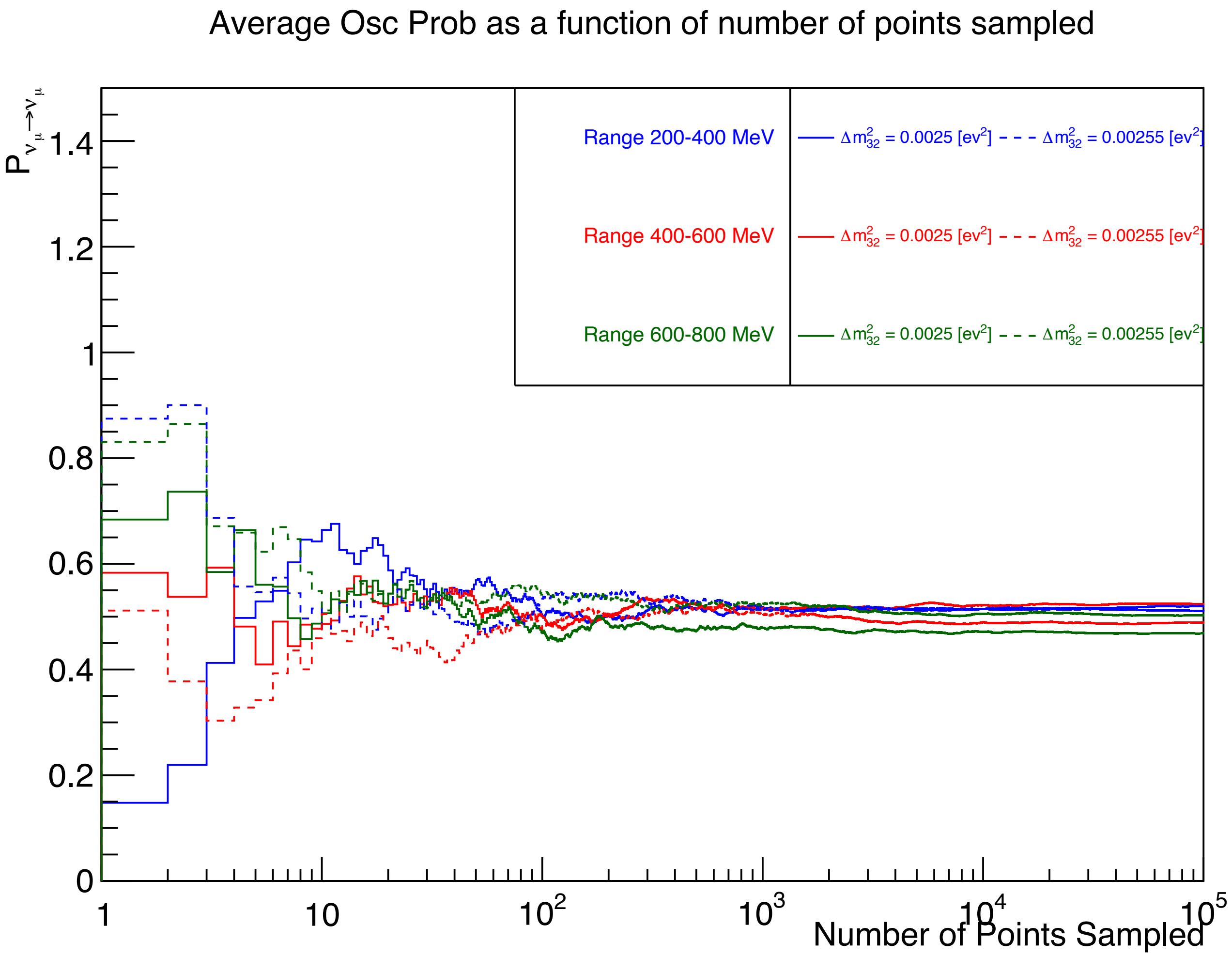
Motivation

- **We are smoothing out the calculated probabilities and thus we get smaller fluctuations for $\Delta m_{32}{}^2$ variation and ultimately smoother contours.**
- **With insufficient statistics, you can have fluctuations in a bin's counts caused by a few outlying events with abnormally large or small oscillation probabilities at certain values of $\Delta m_{32}{}^2$.**
- Increasing the MC statistics would solve this problem and make the contours smoother for $\Delta m_{32}{}^2$.



Motivation

- **For very close values in $\Delta m_{32}{}^2$ the average oscillation probability varies largely, but this affect decreases with increasing sample size.**



- **If the oscillation probability changes fast enough as a function of $\Delta m_{32}{}^2$, we may or may not have "enough" MC energies to fully probe the change in oscillation frequencies.**

- **Increasing the MC statistics, which is what this toy study mimics is impractical, so an alternative way of averaging the oscillation probabilities is required, to smooth the χ^2 distribution.**

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My Approach – Overview

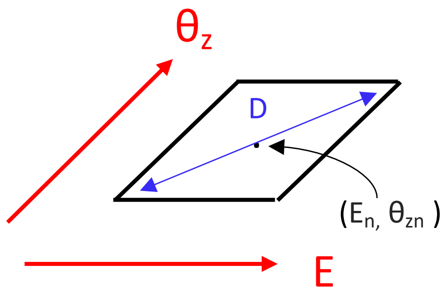
- **I aim to edit the way in which oscillations are applied to the MC and introduce an alternative averaging treatment for SubGeV Upgoing neutrinos.**

Process data and produce MC using Geant3 or Geant4 based software → **Assign types & bins to data and MC events** → **Calculate systematic effects** → **Apply oscillations to MC** **This is where the "Fast Oscillations" are dealt with** → **Calculate χ^2**

- **For bin n, any point in that bin can be described as having coordinates ($E_n + \frac{1}{2}\alpha B_E$, $\theta_{zn} + \frac{1}{2}\beta B_\theta$) where B_E and B_θ are bin widths, and E_n and θ_{zn} are the bin centres of the nth bin. The parameters α and β are just values between -1 and 1.**

- **The goal is to calculate the average value of P in the rectangular bin.**

- **We want to know**
  - **Does the L_{osc} change along the bin**
  - **What is the ratio L_{osc} / D where D is the diagonal of the bin**



- **Where L_{osc} is the characteristic oscillation length for three flavour oscillations in matter, and it it calculated for each event in the bin.**

My Approach – Cases

- Ideally, L_{osc} varies little along the bin, and then things will be easier.

In terms of L_{osc} / D, there are 3 cases:

1. $L_{osc} / D >> 1$

The oscillation probability is approximately flat. The average oscillation probability of the square can be obtained by taking the average of a few points

2. $L_{osc} / D \approx 1$

The most computationally costly scenario. The following 2-D integral must be calculated, and then the result divided by the area of the bin to obtain an average:

$$\iint P \, dE d\theta_z$$

3. $L_{osc} / D << 1$

Neutrino Oscillation decoherence. Take the average over a few points, but using $P_{decoherent}$ instead of just P

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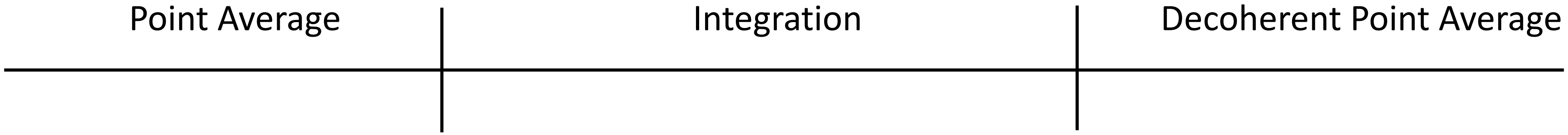
My Approach – Thresholds

- We have

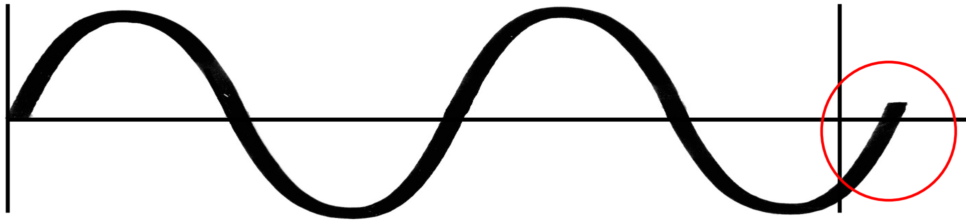


Point Average | Integration | Decoherent Point Average

$L_{threshold\uparrow}$ (α)

$L_{threshold\downarrow}$ (β)

- Where the thresholds of the regimes are functions of the desired maximal uncertainty. Graphically, these uncertainties can be expressed as following (details in backup)



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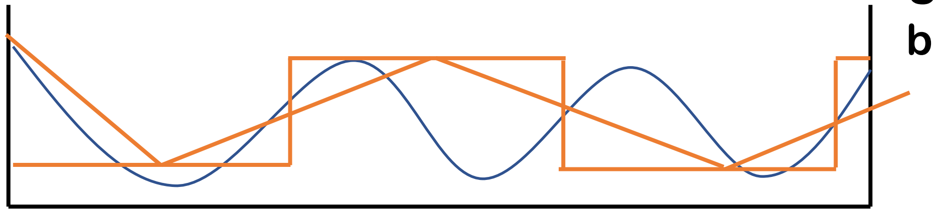
L_{osc} / D << 1 regime



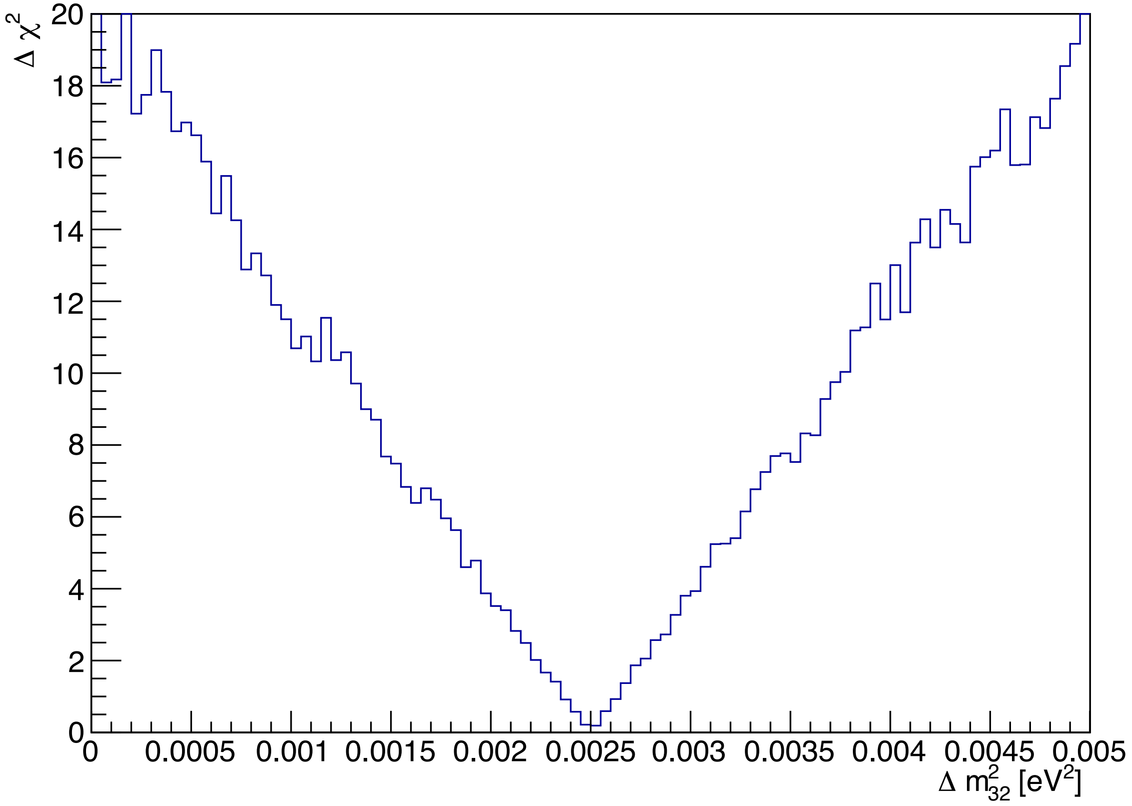
Uncertainty is bound by
|🟧|/|🟦|

L_{osc} / D >> 1 regime

Preliminary Results

- I conducted a preliminary toy study, also using a mock SK4 scenario to test this new approach to probability averaging.

$\Delta\chi^2$ contour for SK4 based toy study



- Preliminary results show some promise; however, the next step is to incorporate this into the full OA pipeline and test this approach more robustly

Summary and Next Steps

- I have presented an overview of atmospheric neutrino oscillations in Super-Kamiokande, and a broad summary of how the atmospheric data is analysed and oscillation parameters extracted.

- One of the current issues with the final χ^2 contours, especially the $\Delta m_{32}{}^2$ parameter, is that they do not vary smoothly as a function of $\Delta m_{32}{}^2$ due to insufficient sampling of the true oscillation distribution.

- Even though the current probability averaging does improve on this jagged feature, it is still not sufficient to remove the jagged edges entirely.

- My alternative approach uses the ratio of L_{osc} / D, separating the binned events based on this ratio, and then applying different oscillation probability averaging prescriptions to each region aims to further smooth the χ^2 contours for $\Delta m_{32}{}^2$.

- Preliminary results based on a toy study indicate an improvement in how smoothly χ^2 varies with $\Delta m_{32}{}^2$.

- Next steps will be to test this study using more robust MC and to eventually incorporate this into the full OA workflow.

- Finally, I will test this approach on actual data and compare with previous published results for the full SK-I – SK-V dataset.

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Thank you for Listening!

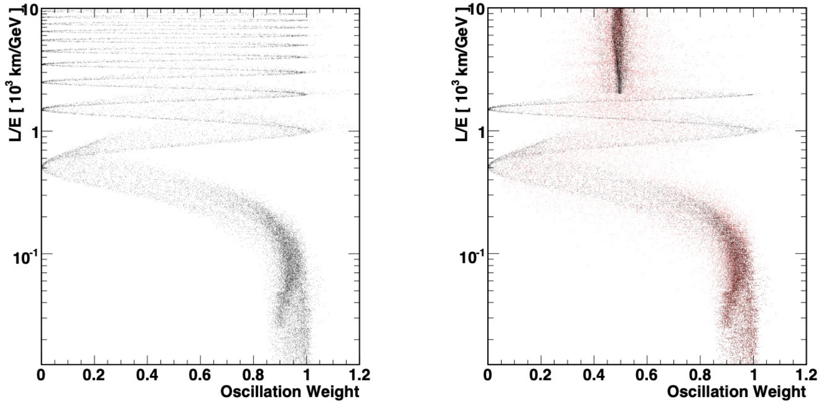
Backup Slides

Current Probability Averaging Treatment Summary

- Nearest Neighbour Averaging aims to smooth the event rate prediction in the “fast oscillation” region. Neighbours are defined as events with the same true neutrino flavour that are in the same reconstructed zenith bin.

- The RMS of the energies of all the neighbours is then found, and the oscillation probability for each event is then calculated five times for when the energy of the event is E, E-RMS, E-(0.5*RMS), E+RMS, E+(0.5*RMS).

- This is repeated for varying path lengths, and so for each event around 20 different oscillation probabilities are calculated which are then finally all averaged over.



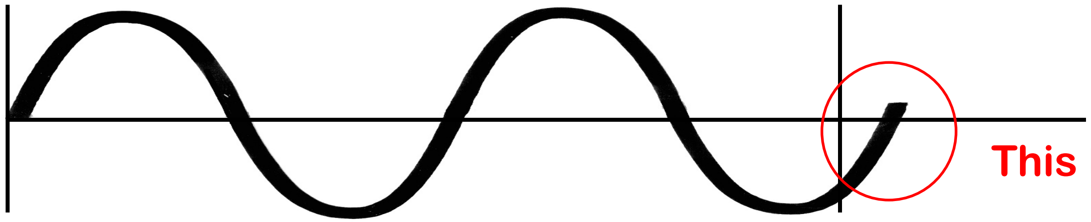
Without averaging

With Averaging

Figure from https://www-sk.icrr.u-tokyo.ac.jp/sk/_pdf/articles/rvw-dissertation.pdf

My Approach – Errors

- In the L_{osc} / D << 1 regime, errors in the calculation of $\langle P \rangle_{bin}$ come from non-integer oscillation period contributions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- This means the maximum possible absolute error (α) is bounded by number of full oscillations in the bin. In particular,

$$\alpha \leq \frac{0.5 \times Amplitude}{n_{osc}}$$

- We want at least the smallest n_{osc} for which the expression is satisfied, so the critical point is

$$n_{osc} = \frac{0.5 \times Amplitude}{\alpha}$$

- We know that as n_{osc} increases, α decreases so we simply need n_{osc} to be larger than the critical value

$$\therefore n_{osc} \geq \frac{0.5 \times Amplitude}{\alpha} \quad \text{where } n_{osc} \propto \frac{D}{L_{osc}}$$

- For example, for a maximum of 1% error in the bin, we need

$$n_{osc} \geq 50 \times Amplitude$$

- We can take the largest amplitude as a worst case scenario (~0.7?) to get $n_{osc} \sim 30$
- We can call the corresponding L_{osc} as $L_{threshold\downarrow}$

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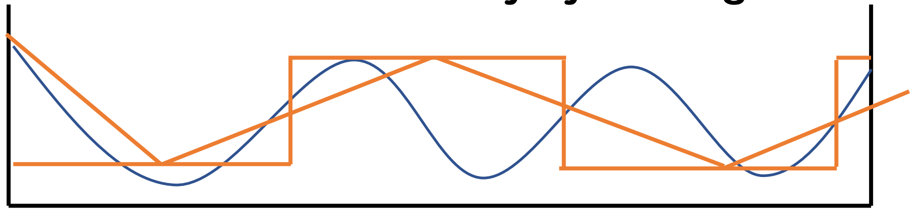
My Approach – Errors

- In the L_{osc} / D >> 1 regime, we can estimate our uncertainty by looking at the difference between a Linear Interpolation of our points and $\sin(L_{osc}\ x)$



Uncertainty is bound by
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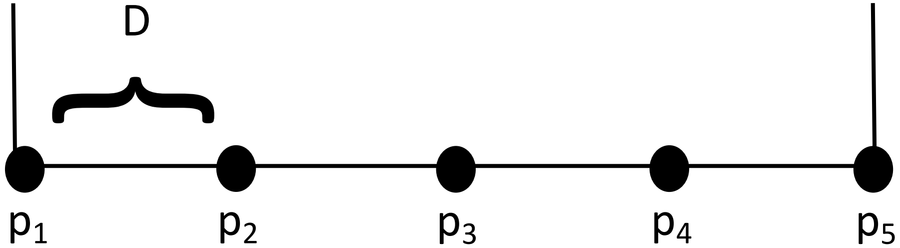
Suppose we have an average of 5 points:



Where D = 1/5 B_w or in general

D = 1/n B_w where n is the number of points

Then our approximated function is

$\sin(p_1\ L_{osc})$ from p_1 to p_1 + D/2
$\sin(p_2\ L_{osc})$ from p_2 - D/2 to p_2 + D/2
…
$\sin(p_5\ L_{osc})$ from p_5 - D/2 to p_5

Then we can calculate the differences analytically, which will give us a function of

$f(L_{osc}$ / D) = |🟧|/|🟦|

And we will find the smallest n_{osc} for which

$f < 0.01$

Call this $L_{threshold\uparrow}$ which is the upper threshold for this regime.

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