Phenomenology of Accelerator and Atmospheric Neutrinos

Group 6

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Understanding Atmospheric Neutrino Data

The Problem

Read the article "Super-Kamiokande Atmospheric Neutrino Results" by T. Toshito, hep-ex/0105023. It contains an old summary of the atmospheric neutrino data. The talk by T. Kajita, presented at the Neutrino 1998 Conference, may also prove helpful in understanding some of the Super-Kamiokande terminology: hep-ex/981001.

1. Numerically calculate and draw histograms of the average muon neutrino survival probability in ten equal-size bins of $\cos\theta_x$ where θ_x is the angle between the neutrino direction and the vertical axis at the detector's location ($\theta_x = 0$ for neutrinos coming straight from above, and $\theta_x = \pi$ for neutrinos coming from below). For simplicity, assume two flavor $\nu_\mu \rightarrow \nu_\tau$ transitions. Make one histogram for $E_\nu = 0.2$ GeV, 2 GeV, and 20 GeV and $\Delta m^2 = 2.5 \times 10^{-4}$ eV^2, 2.5×10^{-3} eV^2, and 2.5×10^{-2} eV^2, for a grand total of nine plots. Assume throughout that the mixing is maximal, i.e., $\sin^2 2\theta = 1$, and that neutrinos are produced 20 km above the surface of the Earth.

2. Look at Figure 1 in the paper and compare with the results you got in part 1. Can you verify that $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$ is a good fit to the data (200 MeV is characteristic of sub-GeV events, 2 GeV is typical of multi-GeV events, and 20 GeV is typical of upward stopping muons. The fourth category, upward through going muons, has an average energy above 100 GeV.)?

3. Use the number of observed sub-GeV "e-like" events (as these seem to agree well with Monte Carlo predictions) to obtain an order of magnitude estimate of the electron neutrino flux (neutrinos per unit time and unit area). The cross section for detecting neutrinos at this energy range is roughly 5 fb.

Super-K

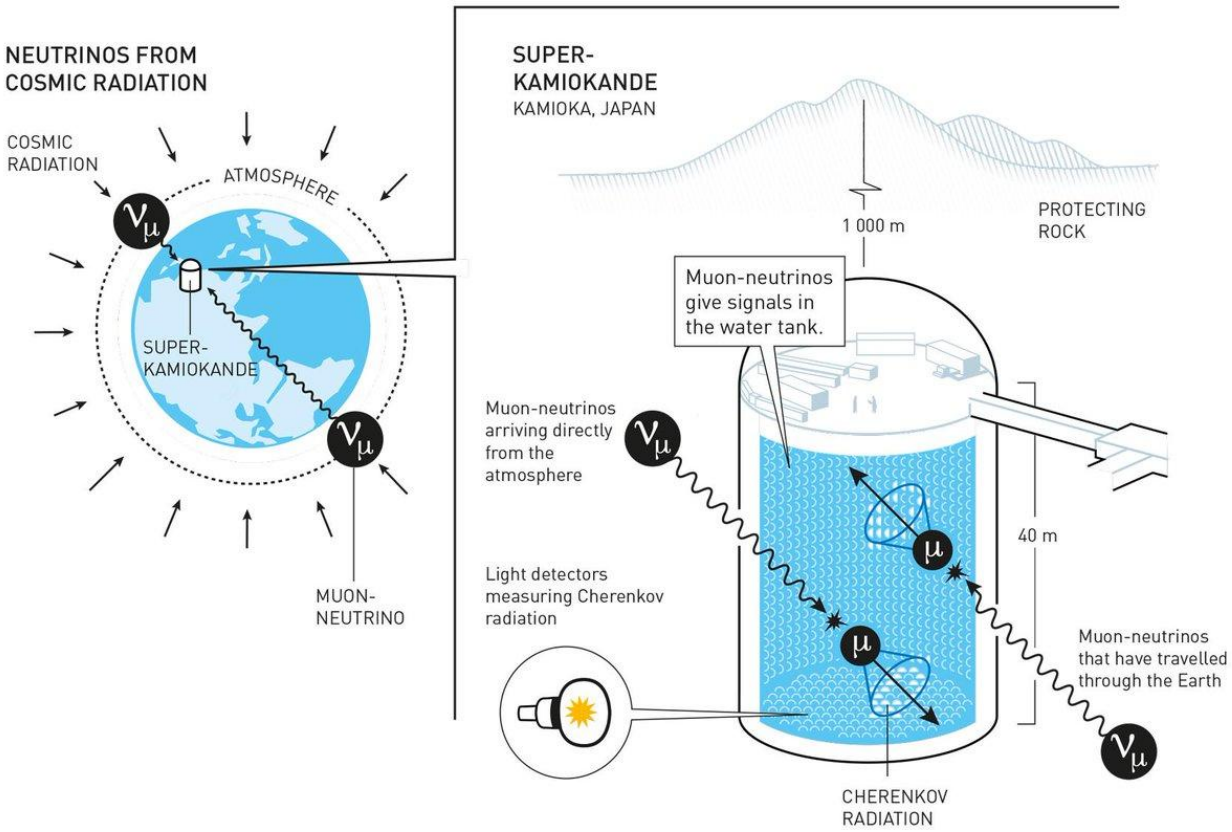

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Survival Probability At Super-K

Muon Neutrino Survival Probability

We use the approximation that there are two flavors of neutrinos: ν_μ and ν_τ

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$$

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Amplitude of the oscillation (which we take to be maximum i.e. 1 in this case)

Difference of the squared masses of the two neutrino species (Given)

Energy of the incoming neutrino (Given)

Muon Neutrino Survival Probability

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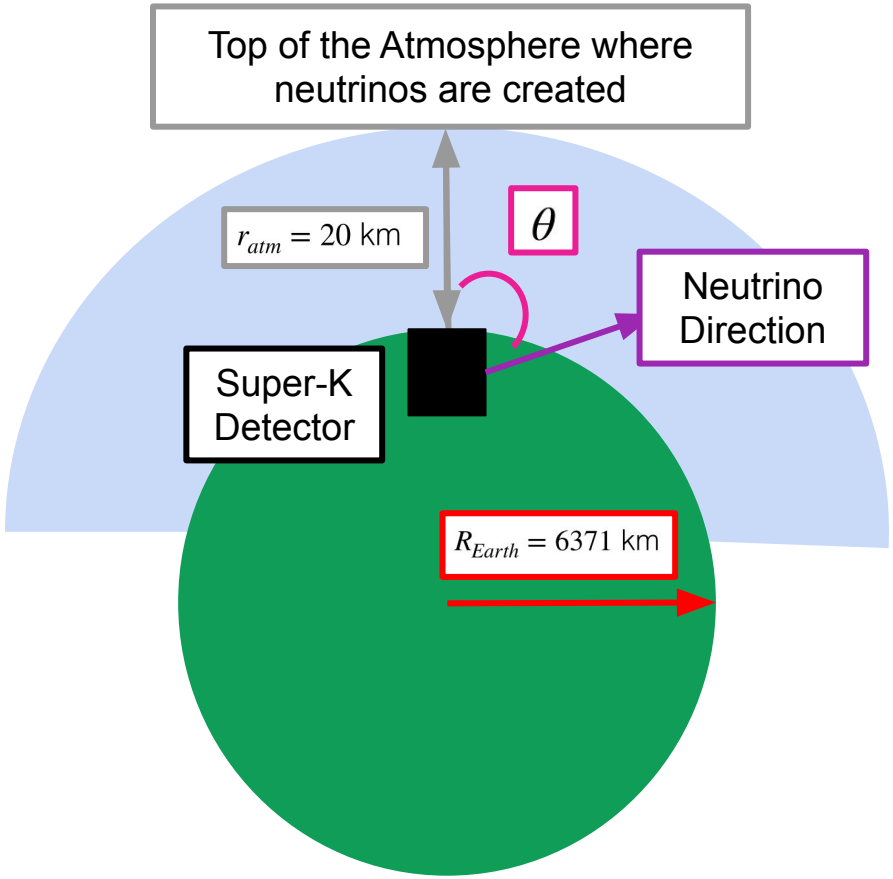
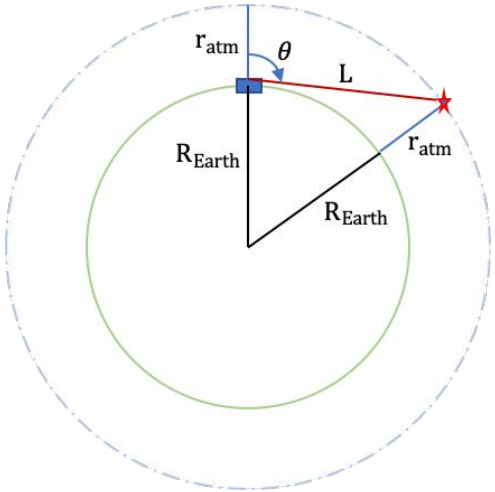
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$$

Length over which the oscillation occurs (i.e. distance from creation to detection). For Super-K, this has a clear dependence on the angle in which the neutrinos enter the detector

Defining the Length of the Oscillation





$$(R_{Earth} + r_{atm})^2 = R_{Earth}^2 + L^2 - 2LR_{Earth}\cos(\pi - \theta)$$

$$L^2 + 2R_{Earth}\cos\theta\, L - r_{atm}^2 - 2R_{Earth}r_{atm} = 0$$

$$\boxed{L(\cos\theta) = -R_{Earth}\cos\theta + \sqrt{R_{Earth}^2\cos^2\theta + 2r_{atm}R_{Earth} + r_{atm}^2}}$$

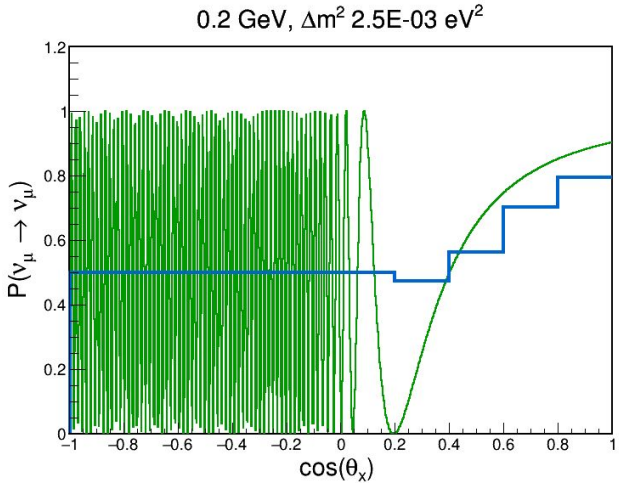
$$L(\cos\theta = 1) = r_{atm}$$

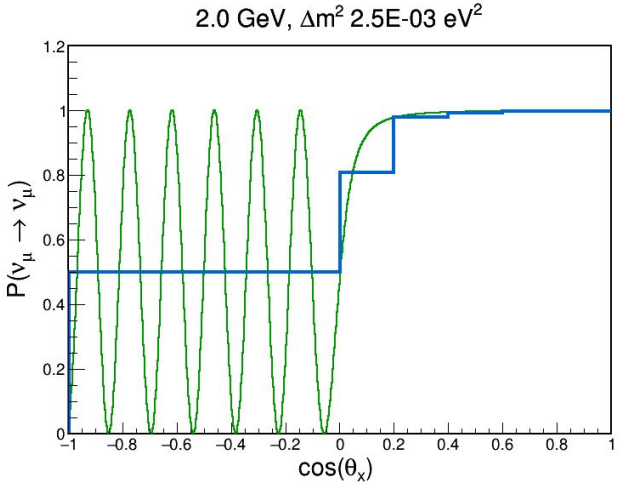
$$L(\cos\theta = -1) = r_{atm} + 2R_{Earth}$$

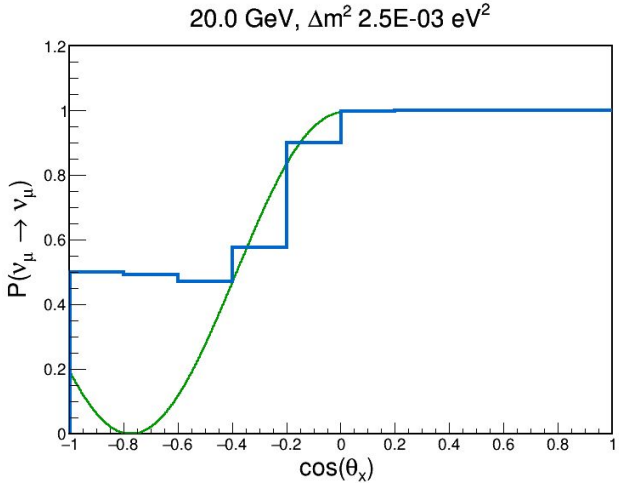
Plots: The Average Probability

$$\langle P_{\nu_\alpha \to \nu_\beta}(L,E)\rangle = \frac{1}{2}\sin^2 2\vartheta \left[1 - \left\langle \cos\left(\frac{\Delta m^2 L}{2E}\right)\right\rangle\right]$$

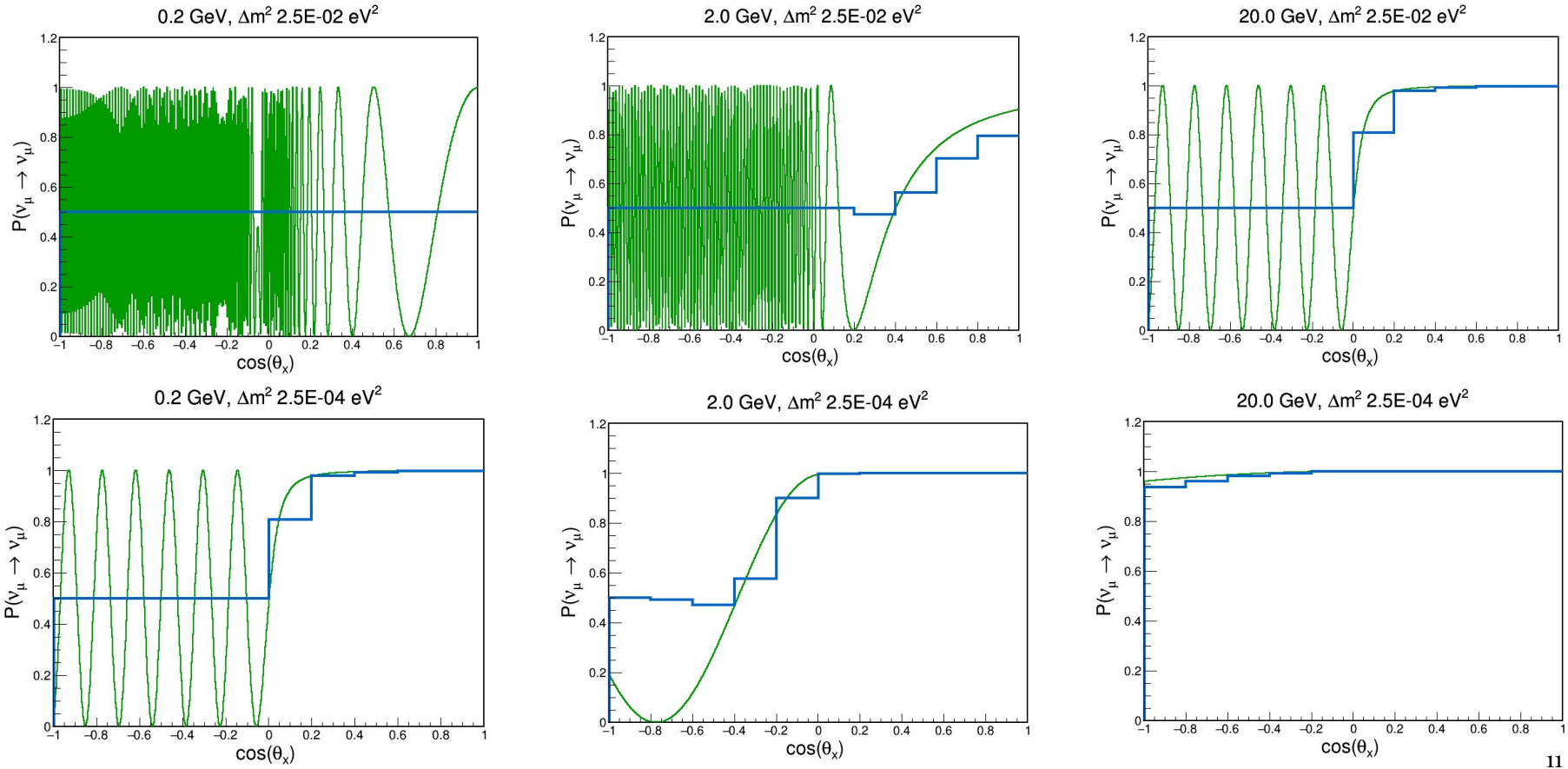
$$\left\langle \cos\left(\frac{\Delta m^2 L}{2E}\right)\right\rangle = \cos\left(\frac{\Delta m^2}{2}\left\langle\frac{L}{E}\right\rangle\right)\exp\left[-\frac{1}{2}\left(\frac{\Delta m^2}{2}\sigma_{L/E}\right)^2\right].$$





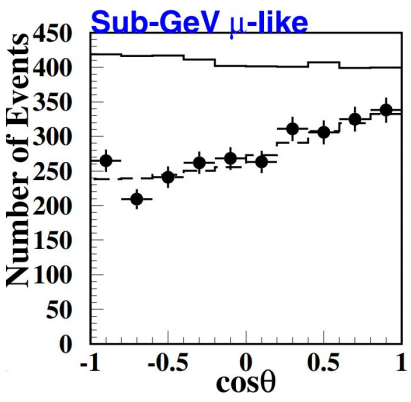


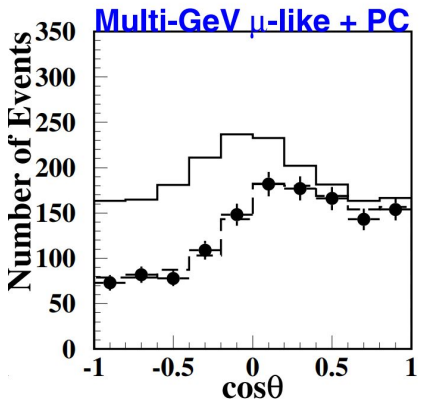
Plots

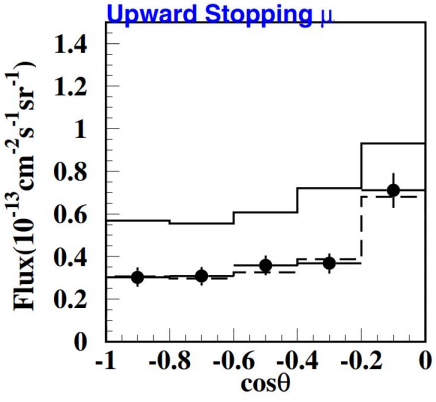

0.2 GeV, Δm² 2.5E-02 eV²
2.0 GeV, Δm² 2.5E-02 eV²
20.0 GeV, Δm² 2.5E-02 eV²
0.2 GeV, Δm² 2.5E-04 eV²
2.0 GeV, Δm² 2.5E-04 eV²
20.0 GeV, Δm² 2.5E-04 eV²
P(νμ → νμ)
cos(θx)

Super-K Results

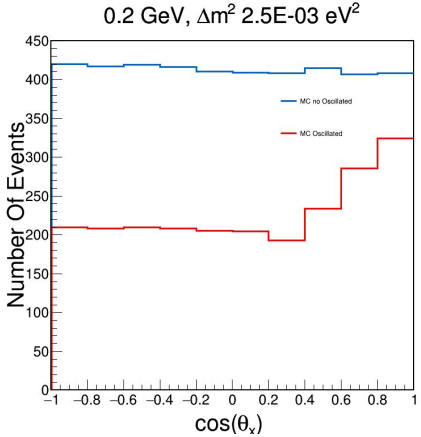
Comparison to the Super-K Results

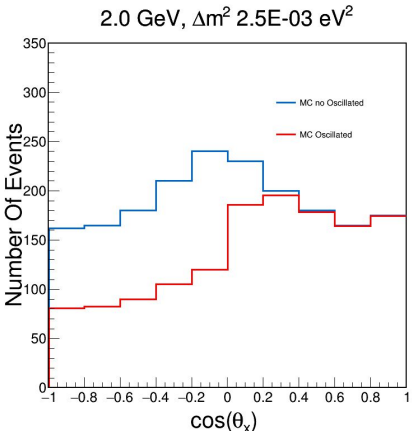


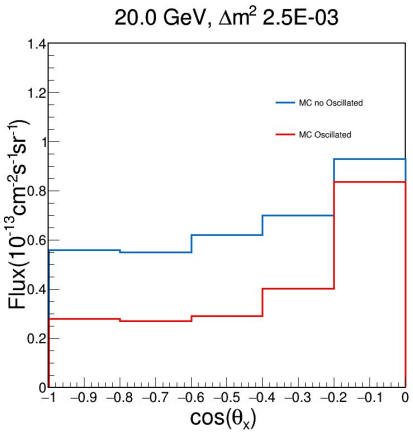




Zenith angle distribution of Super-K data. Also plotted are unoscillated predictions (solid) and predictions accounting for 2 flavor oscillations.hep-ex/0105023



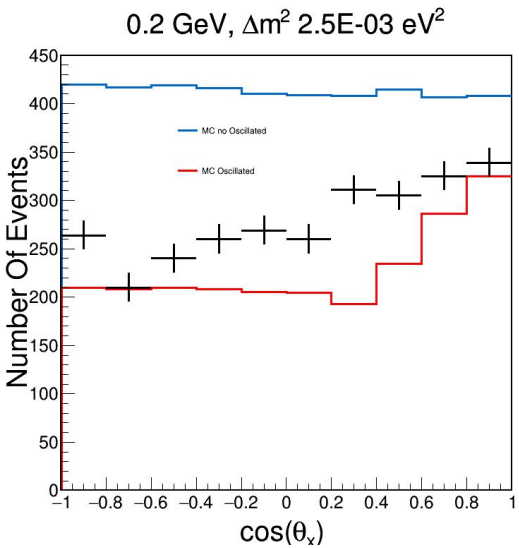


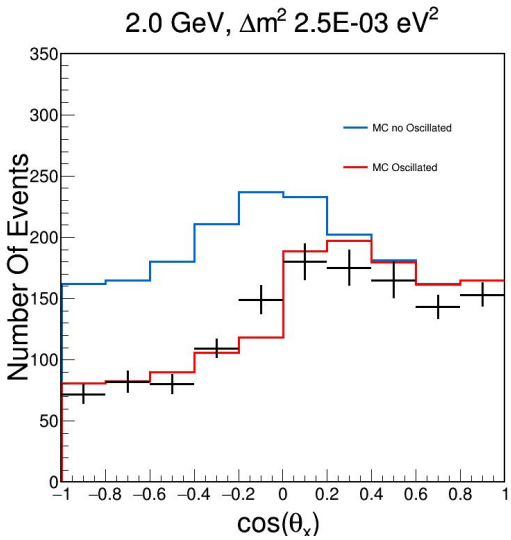


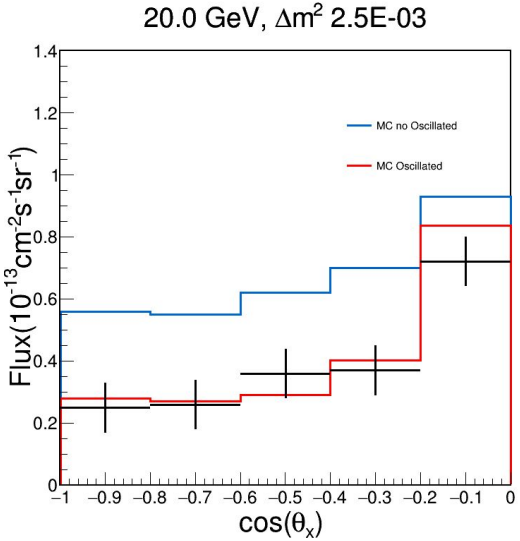
Result of multiply average oscillation neutrino probability (Red) by number of MC unoscillated events (Blue).

Chi Square calculation

Is the data consistent with having been drawn from the prediction?







χ^2 =165.655
P value =2.19829e-30,
Really bad !

Nodf=10

χ^2 =17.0686
P value=0.07286

χ^2 =0.0378627
P value =1

Better Agreement for these two

Electron Neutrino Flux

Electron Neutrino Flux

$$N_{\mathrm{e-like}} = \Phi_{\nu_e} \times \sigma^{\nu N} \times N_{\mathrm{N}}^{\mathrm{SK}} \times T_{\mathrm{N}}^{\mathrm{SK}}$$

$$\Phi_{\nu_e} = \frac{N_{\mathrm{e-like}}}{\sigma^{\nu N} \times N_{\mathrm{N}}^{\mathrm{SK}} \times T_{\mathrm{N}}^{\mathrm{SK}}}$$

$$\boxed{\Phi_{\nu_e} = \frac{N_{\mathrm{e-like}}}{\sigma^{\nu N} \times \frac{m_{fid} N_A}{M_{H_2O}} \times T_{\mathrm{N}}^{\mathrm{SK}}}}$$

$$n = \frac{m}{M} = \frac{N}{N_A} \Rightarrow N_{\mathrm{N}}^{\mathrm{SK}} = \frac{m_{fid} N_A}{M_{H_2O}}$$

$$M_{H_2O} = (2\times1 + 16)\ g/mol = 18\ g/mol$$

$$m_{fid} = 22.5\ kt = 22.5 \times 10^9\ g$$

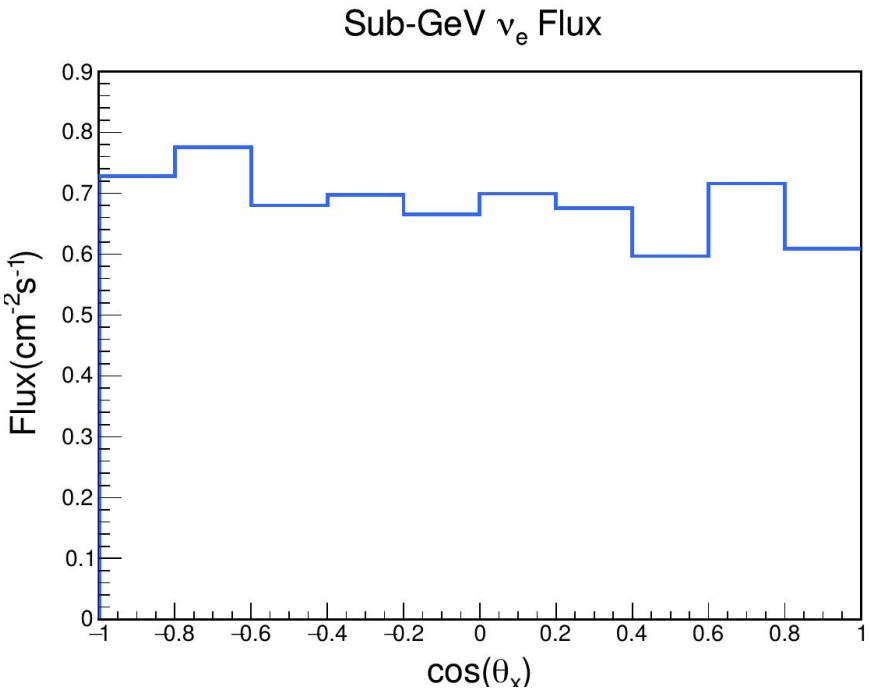
$$N_A = 6.02 \times 10^{23}\ mol^{-1}$$

$$\sigma^{\nu N} = 5\ fb = 5 \times 10^{-39} cm^2$$

$$T_{\mathrm{N}}^{\mathrm{SK}} = 1289\ days = 111369600\ s$$

Electron Neutrino Flux

cosθ	# of Events	Flux ($cm^{-2}s^{-1}$)
0.8 – 1.0	255	6.086E-01
0.6 -- 0.8	300	7.159E-01
0.4 -- 0.6	250	5.966E-01
0.2 -- 0.4	283	6.754E-01
0.0 -- 0.2	293	6.992E-01
-0.2 -- 0.0	279	6.658E-01
-0.4 -- -0.2	292	6.969E-01
-0.6 -- 0.4	285	6.801E-01
-0.8 -- -0.6	325	7.756E-01
-1.0 -- -0.8	305	7.279E-01




That's all Folks!
SUPERB wallpapers