Study the Neutrino Oscillation in Super-Kamiokande

Yang Gao

SA19004005

創寰宇學府 育天下英才
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Motivation

- In the framework of "old" electroweak theory, formulated by Glashow, Weinberg and Salam, lepton flavor is conserved and neutrinos are massless.
- However, various observations have shown that the flavor of neutrinos change upon propagating long distances.

$$|\nu_\alpha(t)>=\sum_{i=1}^{N} U_{\alpha i}^{*} e^{-iE_i t}|\nu_i>$$

- where N is the number of neutrino flavors and U is

$$U=\begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix}\begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13} \end{pmatrix}\begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- So the probability is:

$$P(\nu_\alpha \to \nu_\beta, t) = |<\nu_\beta|\nu_\alpha(t)>|^2 = |\sum_{i=1}^{N} U_{\beta i} e^{-iE_i t} U_{\alpha i}^{*}|^2$$

- For N=2 and ν_e and ν_μ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta_0 & sin\theta_0 \\ -sin\theta_0 & cos\theta_0 \end{pmatrix}\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$E_i = \sqrt{p^2+m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq p + \frac{m_i^2}{2E}$$

Motivation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta_0 & sin\theta_0 \\ -sin\theta_0 & cos\theta_0 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq p + \frac{m_i^2}{2E}$$

- So, we get

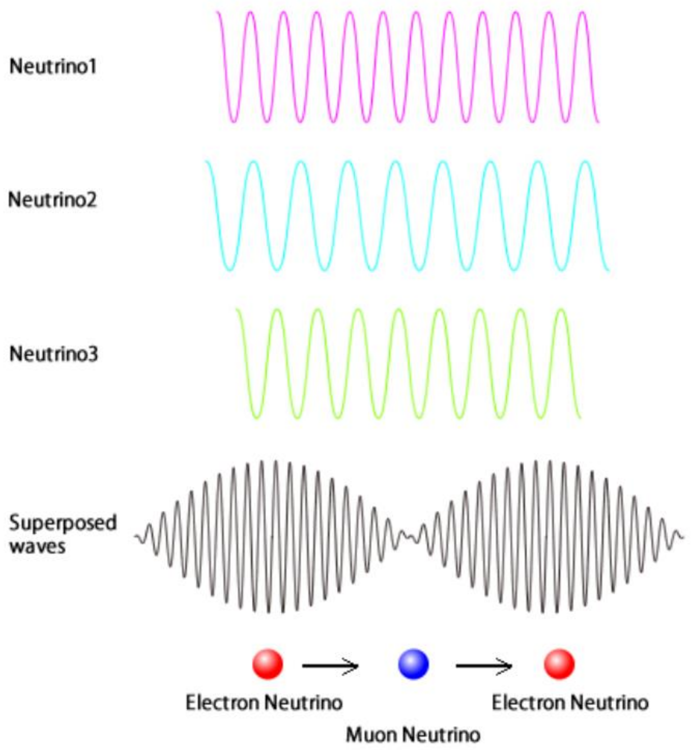
$$P(\nu_e \to \nu_\mu, t) = P(\nu_\mu \to \nu_e, t) = sin^2(2\theta_0) sin^2(\frac{\Delta m^2}{4E} t)$$

- Give a correction of factor:

$$P(\nu_e \to \nu_\mu, L) = sin^2(2\theta_0) sin^2(1.27 \frac{\Delta m^2(eV) L(km)}{E(GeV)})$$

- Where θ is the mixing angle between the mass eigenstates and the weak eigenstates.
- Δm^2 (eV^2)is the difference of the squared mass eigenvalues.
- C is the constant $C = 1.27$.
- L (km)is the neutrinos propagating distances.
- E_ν(GeV) is the energy of the neutrino.

- We can find P is not zero, then Δm^2 is not zero, so the neutrinos are not massless.



The introduction of Super-Kamiokande

- Cylindrical water Cherenkov detector.
- 50-kton of purified water.
- SK has started its observation in 1996.
- The summary of the SK experiments is at Table I.

Phase	Run period	Number of ID PMT	Photo coverage (%)	Analysis energy threshold Total / Kinetic Energy
SK-I	Apr. 1996 – Jul. 2001	11146	40	5.0 MeV / 4.5 MeV
SK-II	Dec. 2002 – Oct. 2005	5182	19	7.0 MeV / 6.5 MeV
SK-III	Jul. 2006 – Aug. 2008	11129	40	5.0 MeV / 4.5 MeV
SK-IV	Sep. 2008 – today	11129	40	(4.5 MeV / 4.0 MeV)

Table 1: Summary of the experimental phases in SK.

- The PMT tubes comprising a photocathode cover about 40%.
- 11,146 Hamamatsu R3600 50cm inner detectors (ID PMTs).
- 1885 outward-facing Hamamatsu R1408 20 cm PMTs (OD).

To reject cosmic ray muons background.

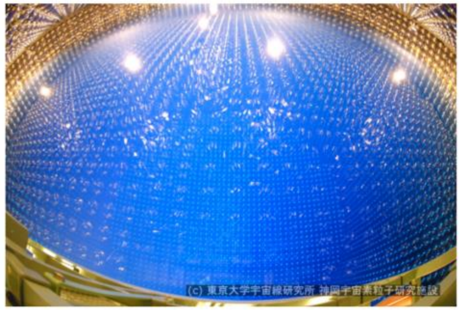
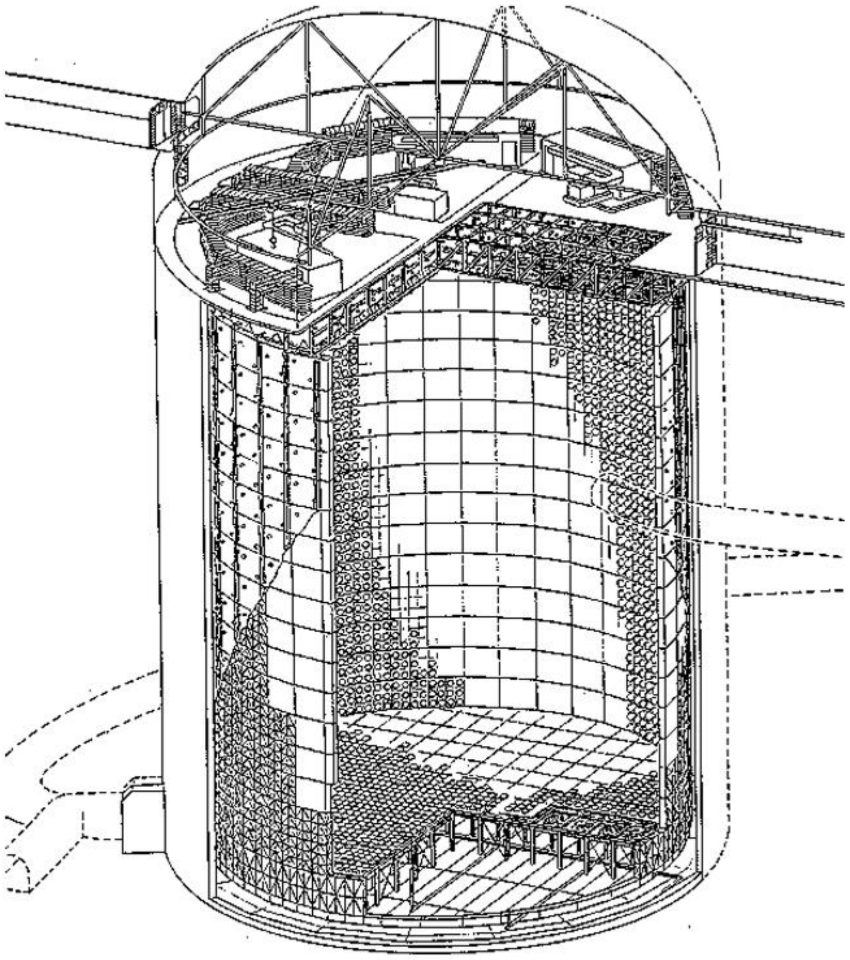


Figure 1: Super-Kamiokande detector during water filling in June 2006.

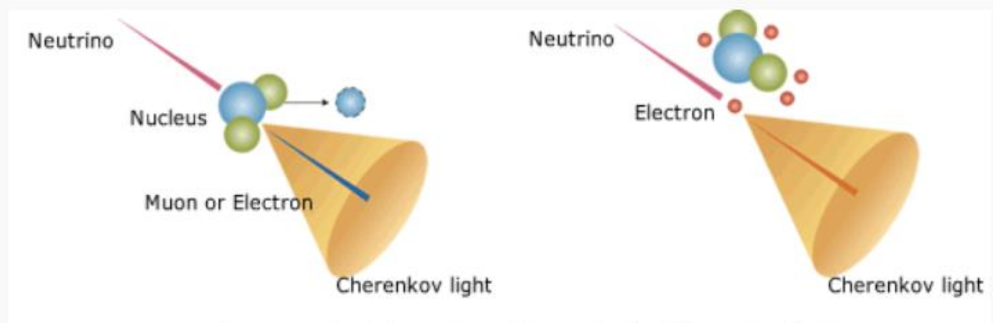
The introduction of Super-Kamiokande

- An event used in analysis is required by the coincidence of at least 30 PMT hits in a 200 nsec window.
- The hit threshold for each individual PMT is about 0.5 pC.
- This trigger condition corresponds to the mean number of hist PMTs for a 5.7 MeV electron.
- The trigger rate is 10-12 Hz.
- The trigger rate due to cosmic ray muons is 2.2 Hz.
- The Cherenkov photons in the detector is simulated with a Monte Carlo program based on the GEANT package.
- For hadronic interactions in water, the CALOR package was employed.



Event reconstruction

- There are four charged and neutral current neutrino interactions are considered:

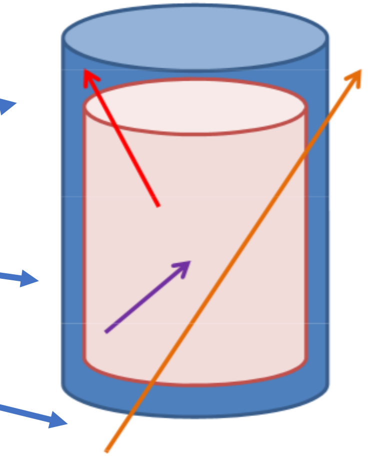


The generated charged particle emits the Cherenkov light.

- ➢ Elastic scattering: $\nu N \rightarrow lN'$
- ➢ Single meson production: $\nu N \rightarrow lN'm$
- ➢ Coherent π production: $\nu O^{16} \rightarrow l\pi O^{16}$
- ➢ Deep inelastic scattering: $\nu N \rightarrow lN'hadrons$

- Where $N\ and\ N'$ are the nucleons (proton or neutron), l is the lepton, and m is the meson.
- If the neutrino interaction occurred in the oxygen nuclei, generated particles like pions and kaons interact with the nucleus before escaping.

- There are four event types:
- ➢ FC(full reconstruction) events.
- ➢ PC(part reconstruction) events.
- ➢ Up-μ events.
- ➢ Stopping-μ events.



Event reconstruction

For example,

- To reconstruct FC events:

✓ (1), Total charge in 300 ns timing window >200 photoelectrons (p.e.).

➢ To reject background from the PMT level.

✓ (2), Less than half of the light in any ID PMT.

➢ To avoid events that most light is detected by just one ID, these background events should be rejected.

✓ (3), Little OD activity.

➢ To make sure this event can’t be from the cosmic ray.

✓ (4), >100 μs window between events.

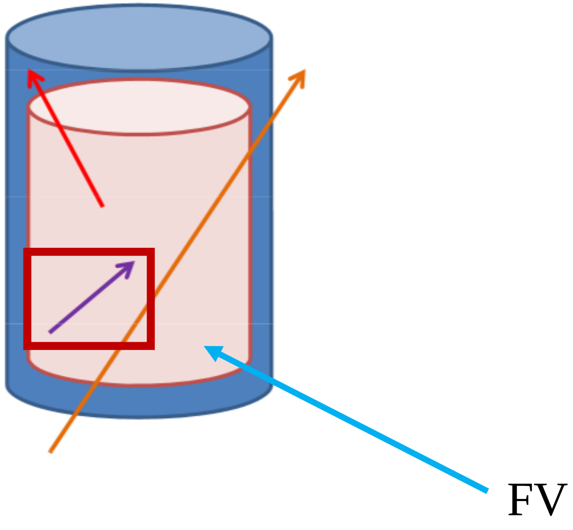
➢ To reject background from different events.

✓ (5), Remove flashers.

➢ To reject background of light from FV.

✓ (6), Inside FV(fiducial volume) with at least 30 MeV visible energy.

➢ To improve the significance of signal.



Event reconstruction

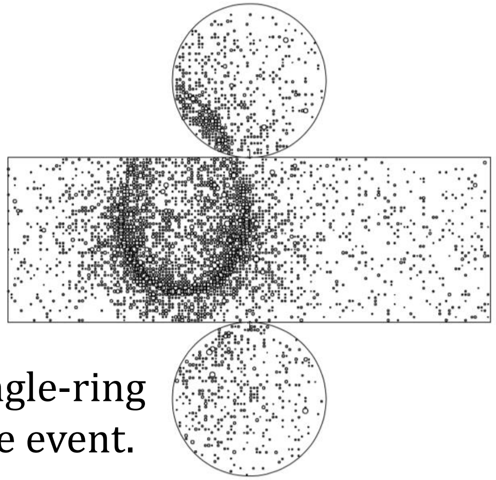
- There are some brief steps to reconstruct the events:

➢ (1), search for an event with a single Cherenkov ring of a lepton produced by neutrino charged or neutral current interaction.

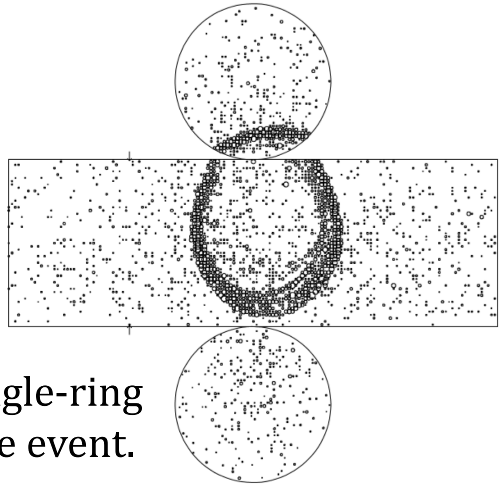
➢ (2), classify the ring into two categories, e-like and μ-like, using the photon distribution of the ring pattern.

➢ (3), reconstruct the momentum and direction of the lepton using the observed ring image.

- Details for every type are shown in paper.



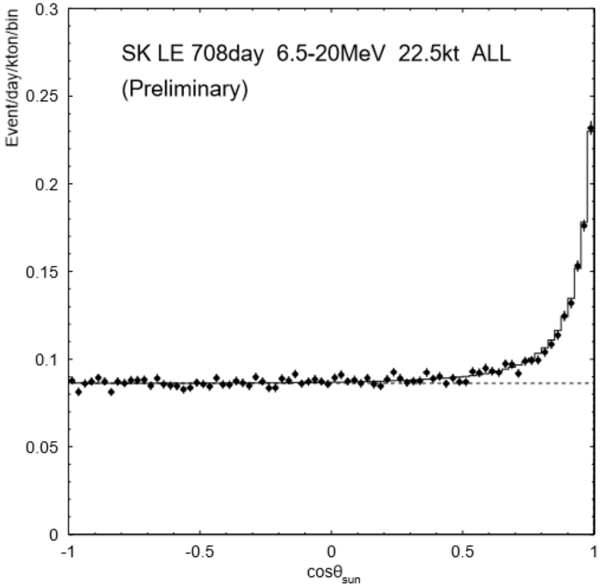
A single-ring e-like event.

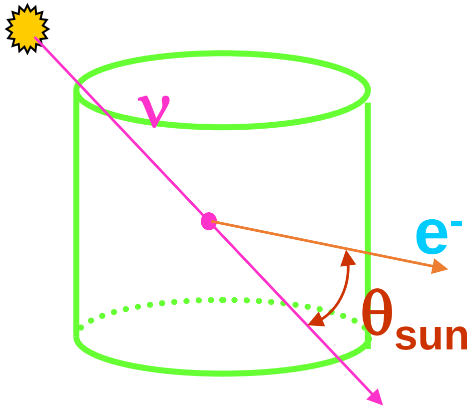


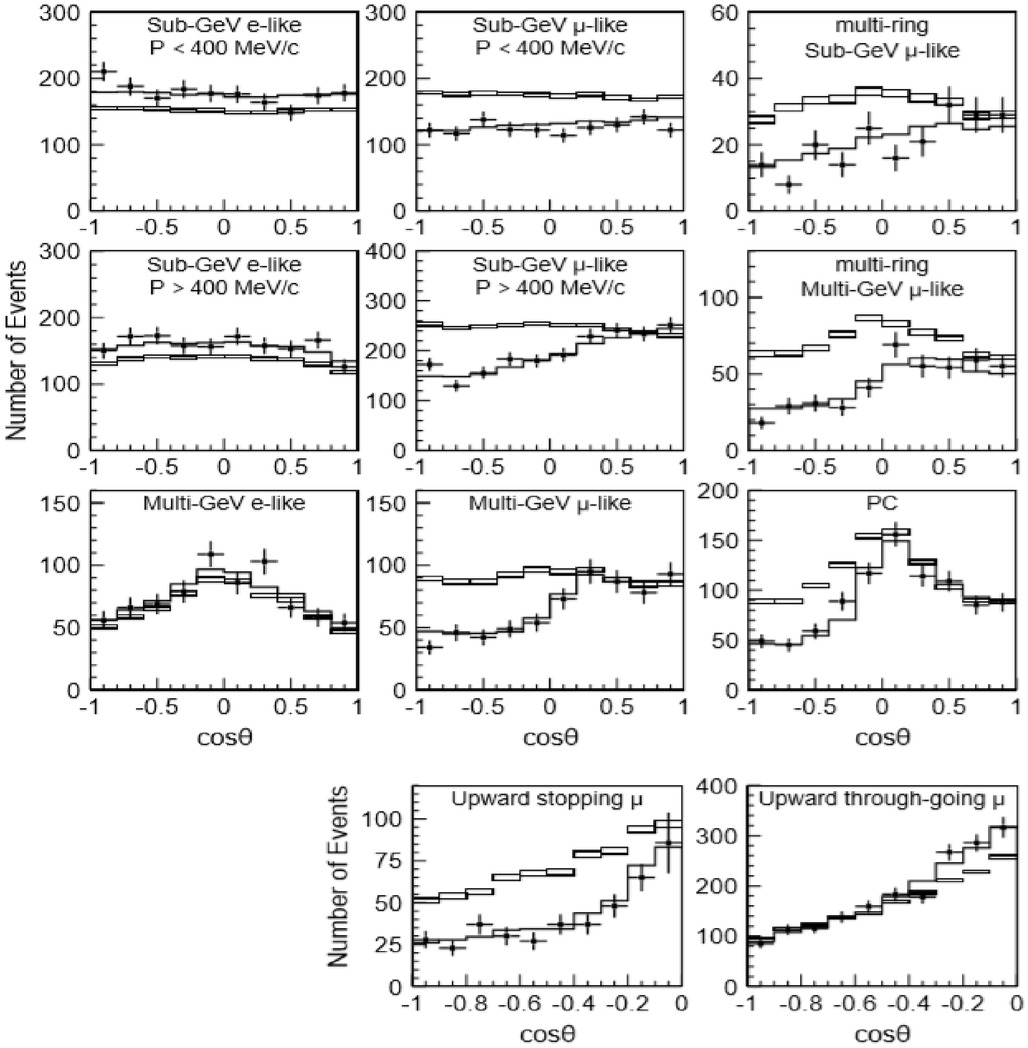
A single-ring μ-like event.

Results Analysis

- This is signal distribution in zenith angle spectrum. The points show the data, the box histograms show the non-oscillated MC and the lines show the best-fit expectations for $\nu_\mu \leftrightarrow \nu_\tau$.
- The zenith angle (θ_{sun}) is shown in picture below:
- The left picture shows super-K can detect the zenith angle pretty good from solar neutrino.
- $\Delta {m_{23}}^2 = 2.19^{+0.14}_{-0.13} \times 10^{-3}\text{eV}^2, sin^2 2\theta_{23} > 0.96(90\%)$ C.L.

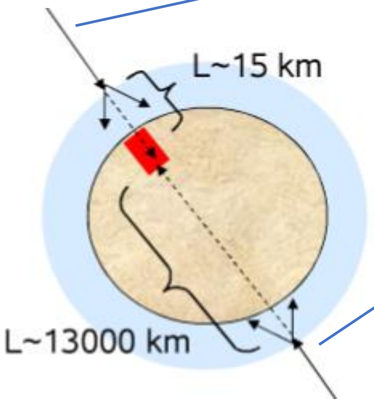




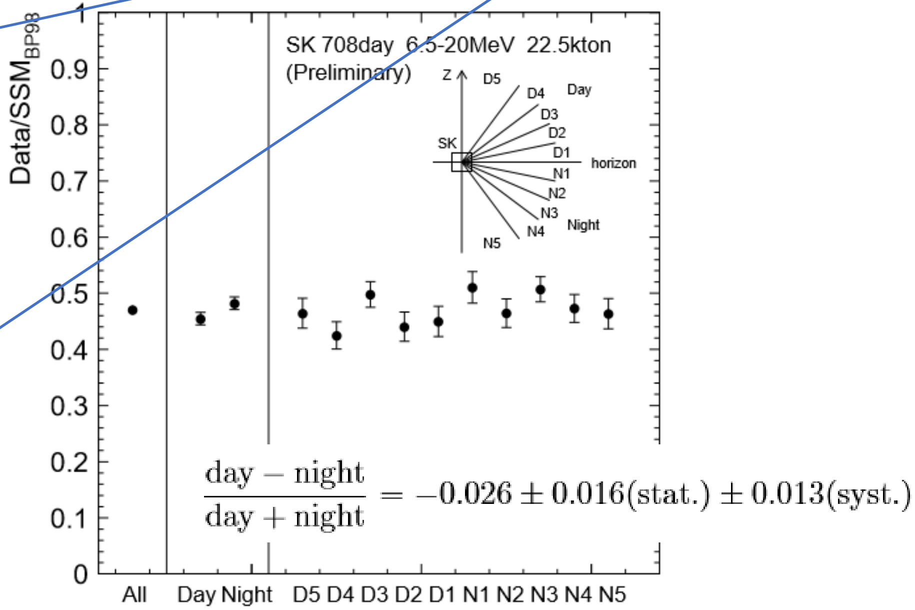


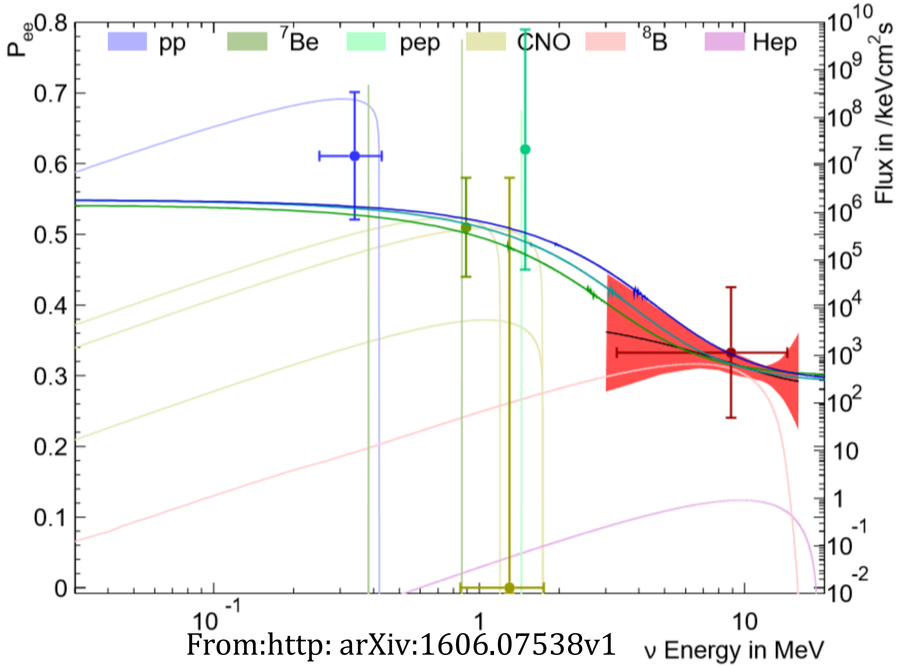
MSW(Matter-enhanced neutrino oscillations)

- Even if all neutrinos are massless it is possible to have oscillations occur when neutrinos pass through matter in theory.(Phys. Rev. D 17, 2369 (1978)).
- The right picture shows the solar neutrino interact with the matter.
- The middle picture shows the different numbers during night and day.



From:http: arXiv: hep-ex/9903034v1 16 Mar 1999





From:http: arXiv:1606.07538v1 [hep-ex] 24 Jun 2016

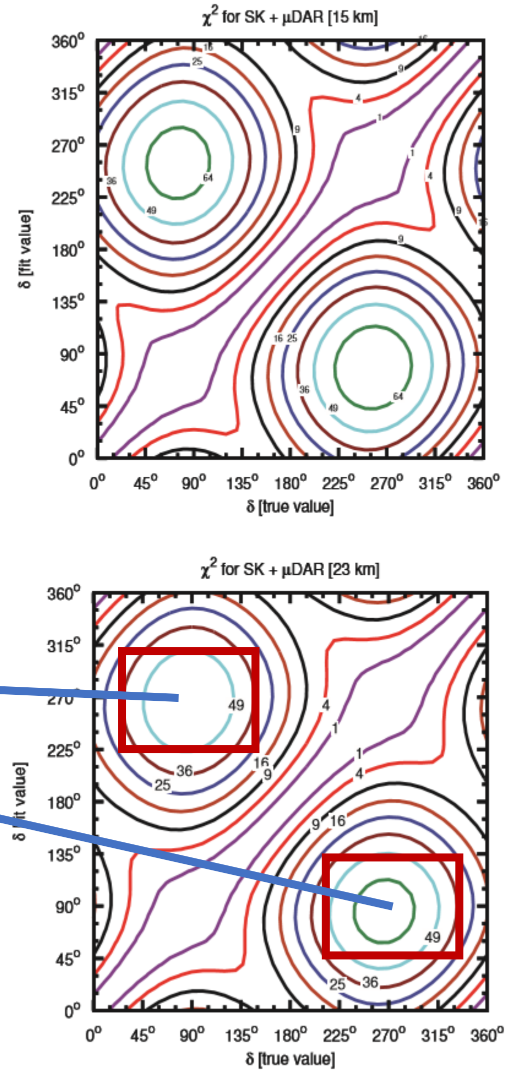
Other results in Super-K

Brief CP-violation results in Super-K

- X-axis is trial value of the best fit δ.
- Y-axis is the theoretical spectra of δ_{true}.
- The line shows the different χ^2.

- For 23 km baseline, there is a CP-violation at $\delta = 90°$ or $270°$.

✓ Maximum deviation during fit the theory.
✓ CP-violation may appear at here.



Other results in Super-K

Brief proton decay results in Super-K

- Four tagged modes used here:

✓ $p \to e^+e^+e^-$

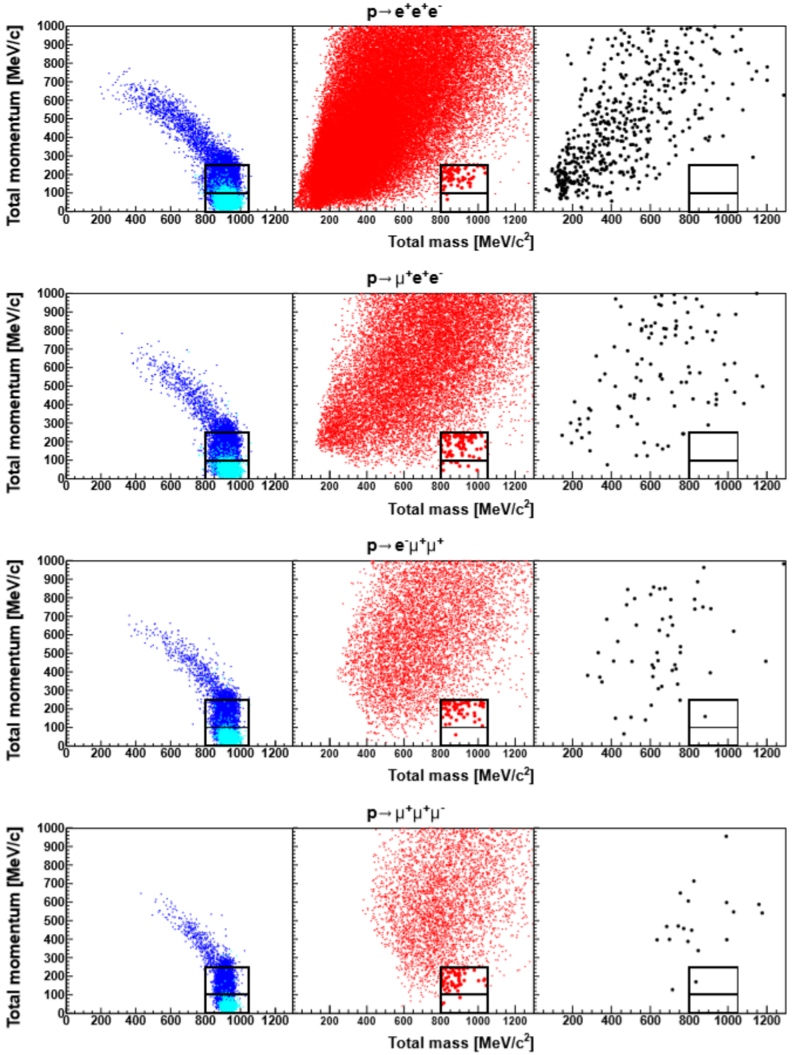
✓ $p \to \mu^+e^+e^-$

✓ $p \to \mu^+\mu^+e^-$

✓ $p \to \mu^+\mu^+\mu^-$

- The right picture shows two dimensional plots of total mass and momentum for signal (left), background (center) and measured data (right).
- Only $p \to \mu^+\mu^+e^-$ and $p \to \mu^+\mu^-\mu^+$ has one event and from the table, these two events may be background events.
- Finally there is no proton decay signal found.

Modes	Background (events)	Candidate (events)	Probability (%)	Lifetime limit ($\times 10^{34}$ years) at 90% CL
$p \to e^+e^+e^-$	0.58 ± 0.08	0	-	3.4
$p \to \mu^+e^+e^-$	0.50 ± 0.06	0	-	2.3
$p \to \mu^-e^+e^+$	0.50 ± 0.06	0	-	1.9
$p \to e^+\mu^+\mu^-$	0.27 ± 0.04	1	18.4	0.92
$p \to e^-\mu^+\mu^+$	0.27 ± 0.04	1	18.4	1.1
$p \to \mu^+\mu^+\mu^-$	0.40 ± 0.07	1	25.8	1.0



Summary

- Give a brief talk about motivation
- Give a talk about Super-K and the method of reconstruction.
- Finally, give some simple results in Super-K:
- (1), For neutrino oscillation: $\Delta {m_{23}}^2 = 2.19^{+0.14}_{-0.13} \times 10^{-3}\mathrm{eV}^2$, $sin^2 2\theta_{23} > 0.96(90\%)$ C.L.
- (2), For MSW neutrino oscillation : $\frac{day-night}{day+night} = -0.026 \pm 0.016(stat.) \pm 0.013(\mathrm{syst.})$
- (3), For CP-violation: there is a CP-violation at $\delta = 90°$ or $270°$.
- (4), For proton decay: there is no proton decay signal found.

That's all, Thanks!