Neutrino Oscillation; Results from Super-Kamokande

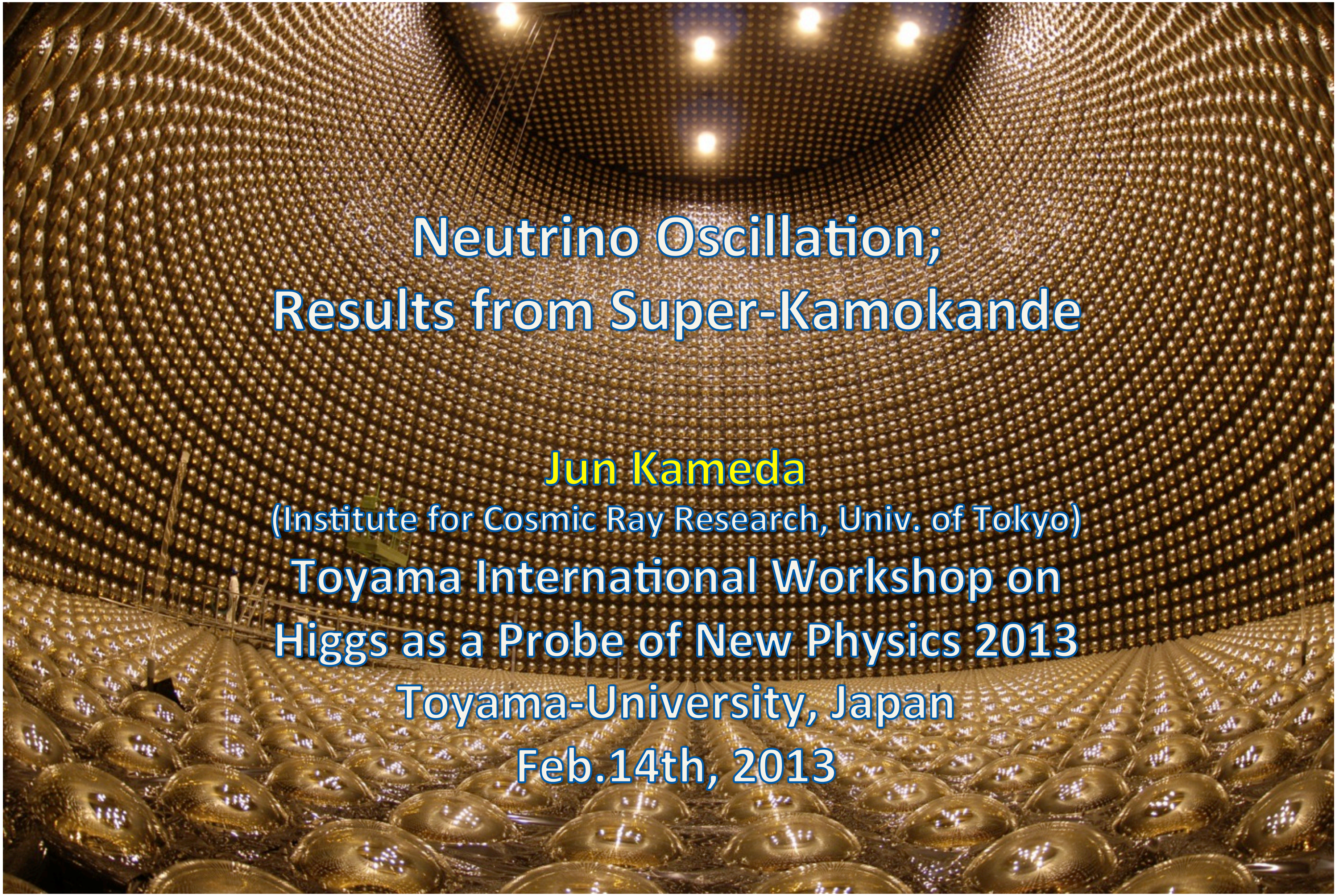
Jun Kameda

(Institute for Cosmic Ray Research, Univ. of Tokyo)

Toyama International Workshop on Higgs as a Probe of New Physics 2013

Toyama-University, Japan

Feb.14th, 2013



Outline

- Recent results on Neutrino Oscillations in Super-Kamiokande
  - Atmospheric neutrinos
  - Long baseline experiment (T2K)
  - Solar neutrino
- Future prospects in Kamioka

Introduction: Neutrino Oscillation

Flavor eigenstates are Mixture of the mass eigenstates

2-flavor case:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

α, β = flavor states
1,2 = mass states

Probability that ν_α is ν_α after flight L:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2(\Delta m^2 L/4E)$$

θ : mixing angle
L : flight distance
E : neutrino energy
m_i : neutrino mass

$\Delta m^2 = m_2^2 - m_1^2$:difference of squared mass

Neutrino Oscillation is induced by mixing of states and finite masses

Neutrino flavors and mixing

(Maki-Nakagawa-Sakata-Pontecorvo Matrix)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\alpha i}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Flavor eigenstates

Mass eigenstates

Atmospheric ν,
Accelerator ν experiments
(K2K, MINOS, T2K..)

$\theta_{23} \sim 45°$
$\Delta m^2_{23} \sim 2.4\times10^{-3}(eV^2)$

Reactor ν,
Accelerator ν,
Atm. ν

$\sin^2 2\theta_{13} \sim 0.1$

Solar ν,
Reactor ν

$\theta_{12} \sim 34°$
$\Delta m^2_{12} \sim 8\times10^{-5}(eV^2)$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\cdot\sum_{i>j}\mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\cdot\sin^2\Phi_{ij} \pm 2\cdot\sum_{i>j}\mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\cdot\sin^2 2\Phi_{ij}$$

$$\Phi_{ij} = \Delta m^2_{ij}L/4E$$

3 oscillation scale、Oscillation amplitude induced by 3 mixing angle

Imaginary part can only accessed by appearance channel ($\alpha\neq\beta$)

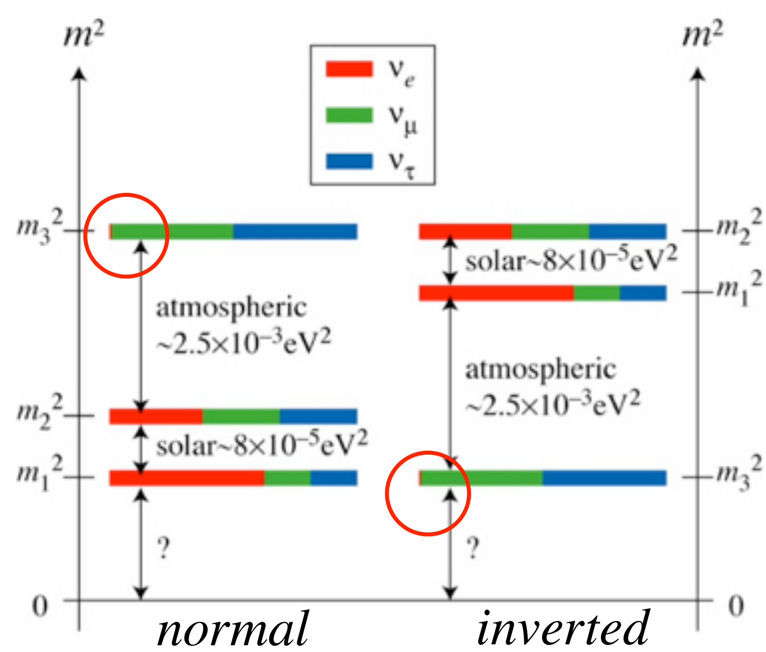
What is unknown

CP violation (δ_{cp})

Mass hierarchy

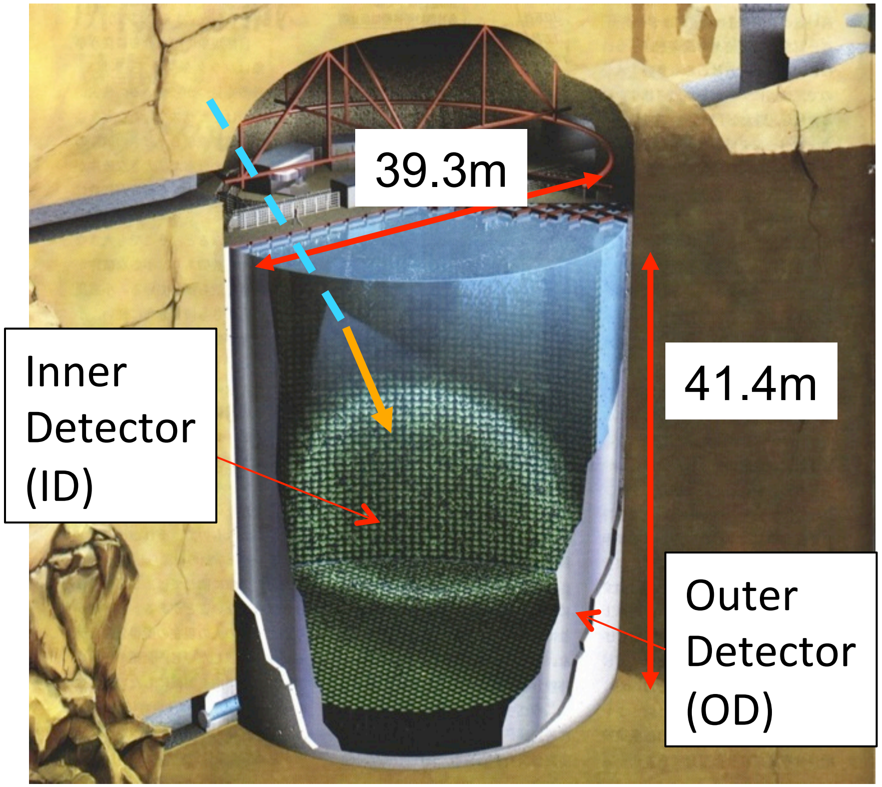
- Neutrino Oscillation induced by the difference of masses. Only we know is that two different size of scale exists

→Two hierarchy can exist



Study of neutrino oscillation in various channels can give answer to these questions

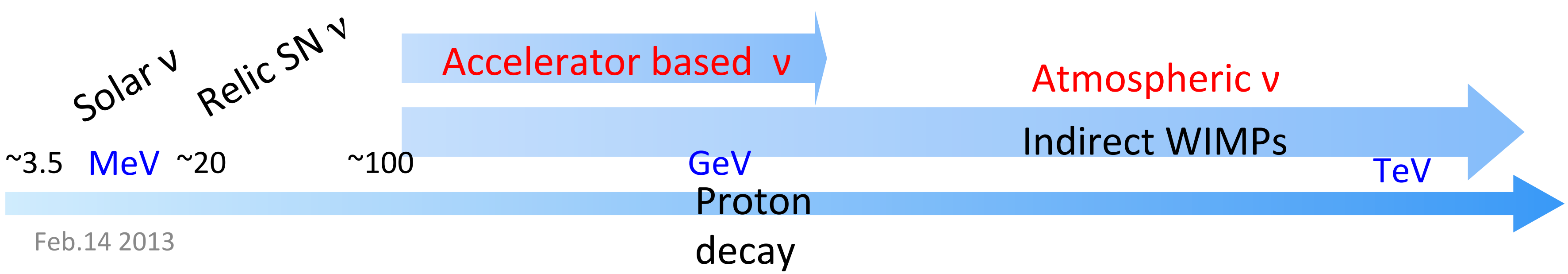
Super-Kamiokande IV



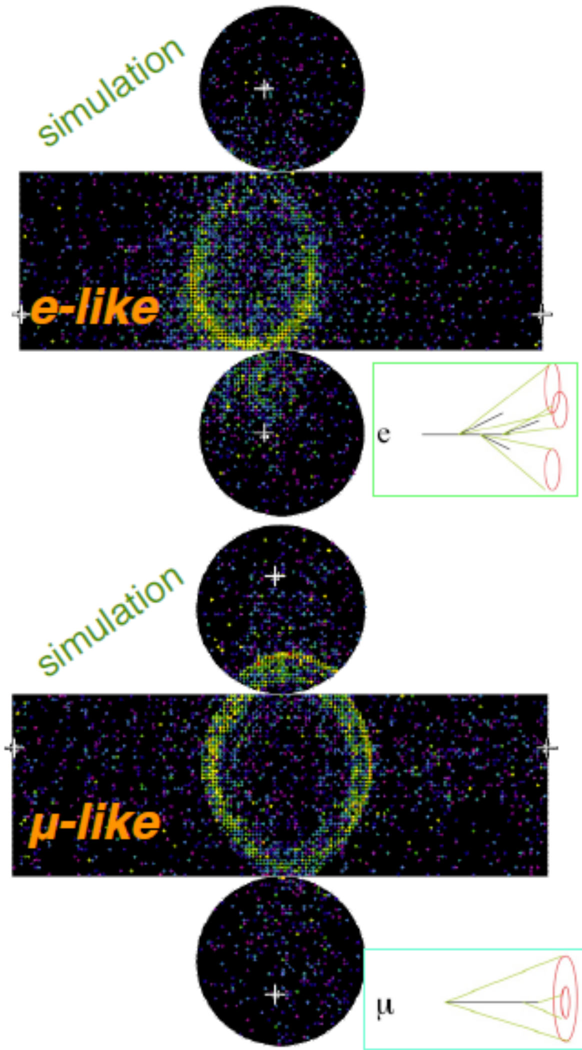
- Ring-imaging Water Cherenkov Detector, located at Kamioka-Mine, Gifu-pref. Japan
  - 1km overburden
  - Cosmic ray reduces ~ 10^{-5} at surface
- 22.5kton Fiducial Volume.
  - Inner Detector (ID) :11,129 20inch PMT
  - Outer Detector(OD):1,885 8inch PMT
- SK-I had started 1996.
- SK-IV with deadtime-less DAQ : 2008~

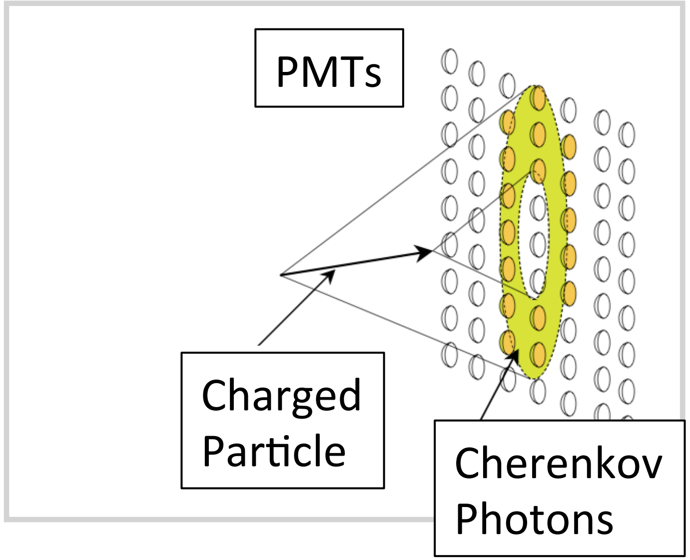
- 4π acceptance, very efficient π^0/e separation.
- High Particle ID (μ/e) power (~99% at 600MeV/c)
- Good energy reconstruction.

Very wide Energy range, Multi Physics targets:



Reconstruction of events

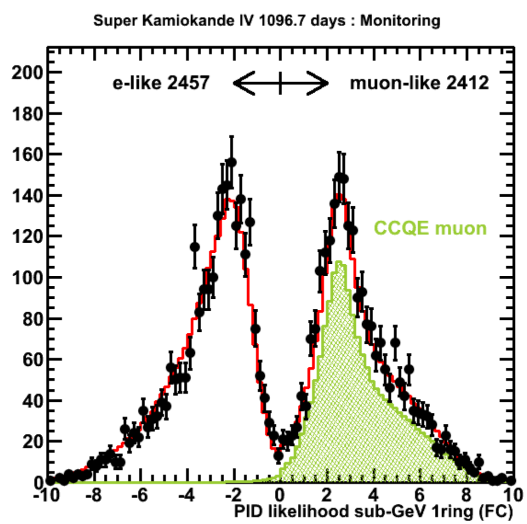




- # of hit PMTs
- PMT hit timing
- Intensity of Photon (P.E.s)

↓

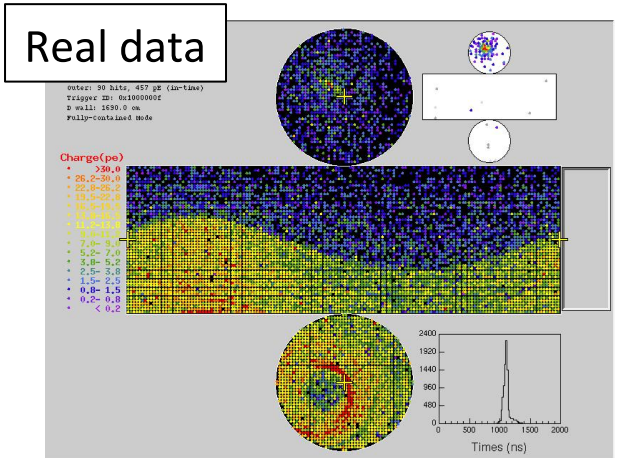
- Event vertex
- Direction of particle
- Particle species,
- Energy

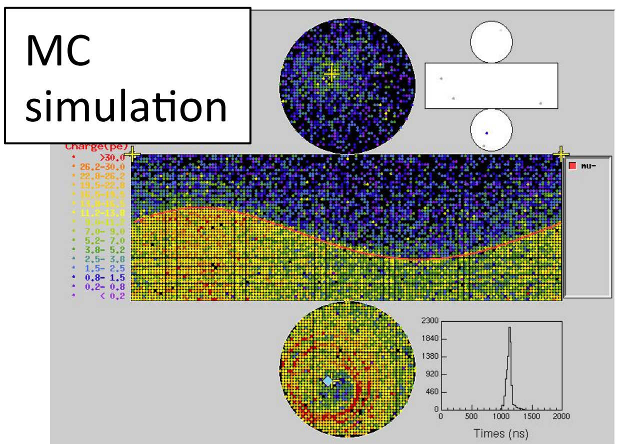


Particle Identifier

- Particle Identification is a key issue for neutrino flavor oscillation.
- Pattern & opening angle of Cherenkov cone are used
- Mis-ID probability ~ 1% (well tested by atm.ν, cosmic μ)

Calibration of the detector



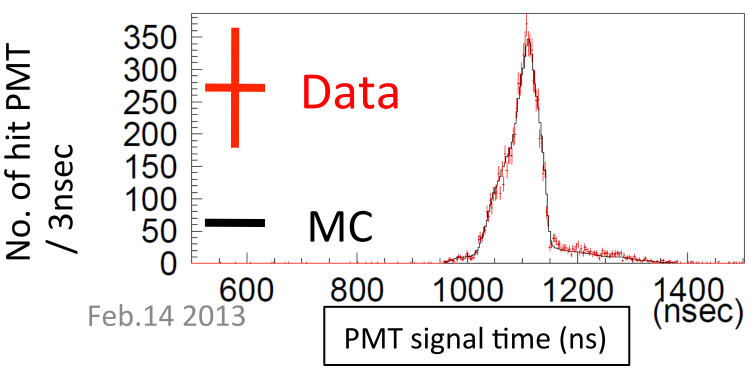


Detailed Calibration works has been done intensively with in-situ & ex-situ sources: (pulse laser, CRμ, electron LINAC, ..)

- Timing response of PMTs
- Gain of PMTs
- Water transparency measurement
- Detector Uniformity …

Well test the event reconstruction performance

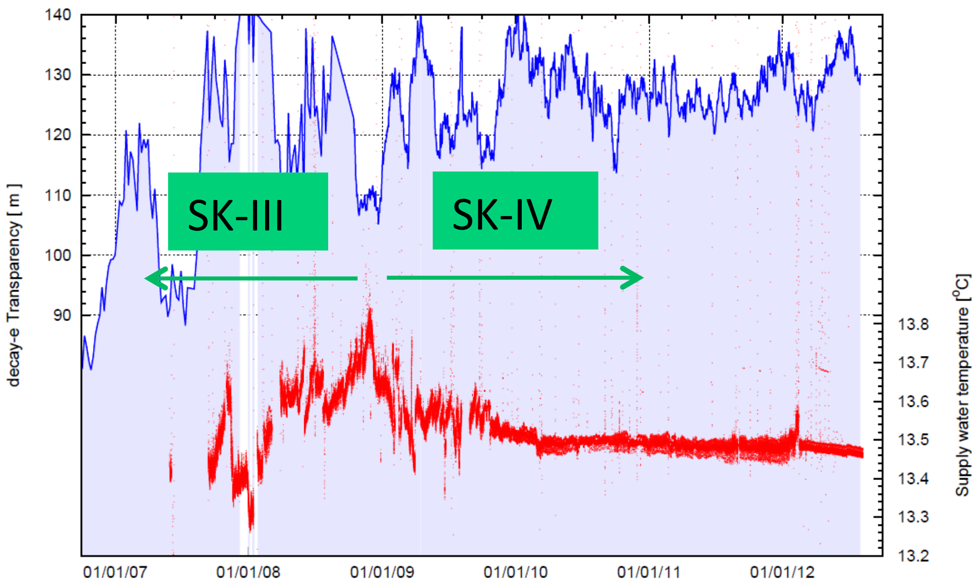
- Vertex, direction
- Particle identification
- Energy reconstruction, …

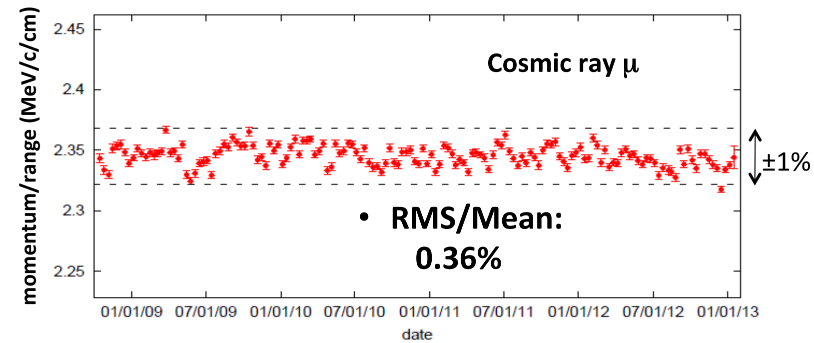


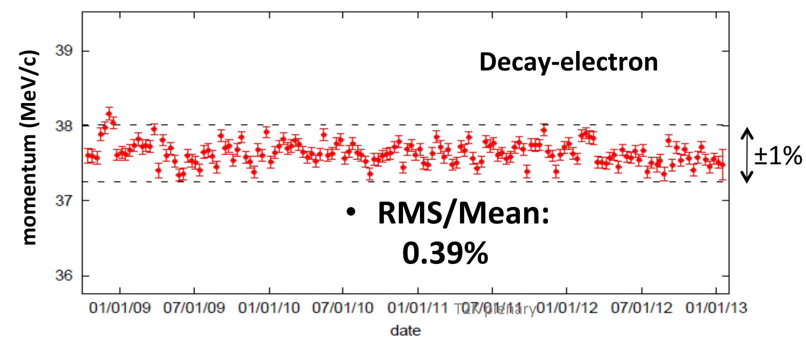
Full Monte Carlo (MC) simulation has been developed based on measurements of fundamental parameters & available models.

Stability

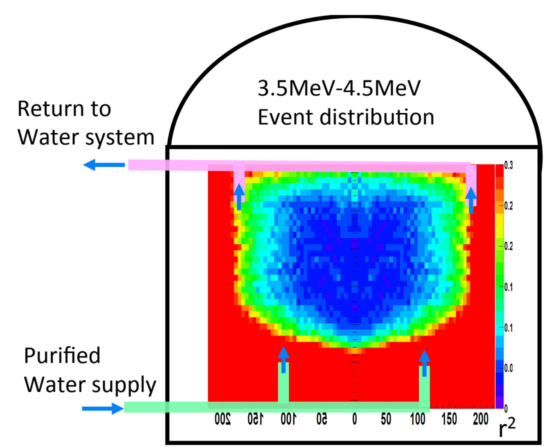
Key issue is a water quality.







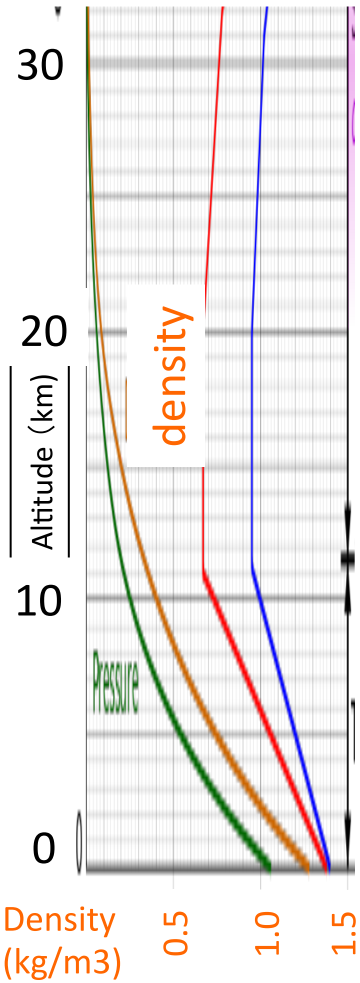
- Keep water quality by continuous purification of the water.
- Carefully control the flow inside Super-K
- Water transparency is continuously monitored and taken into account in event reconstruction.
- 1% level stability of energy estimation.

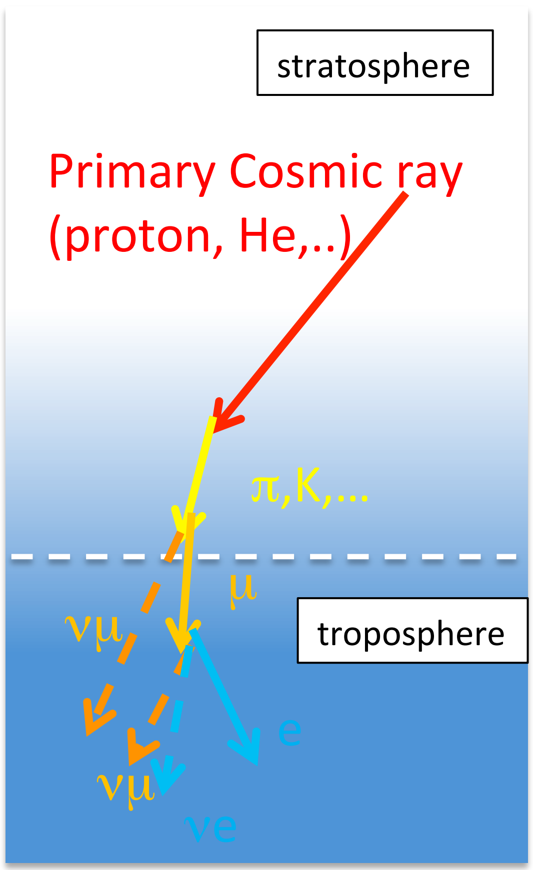


Study of neutrino oscillation on atmospheric neutrinos

Atmospheric neutrinos

= Secondary cosmic rays produced in the atmosphere





λ~40g/cm² for proton
→L~15km

p + A → π's, ...

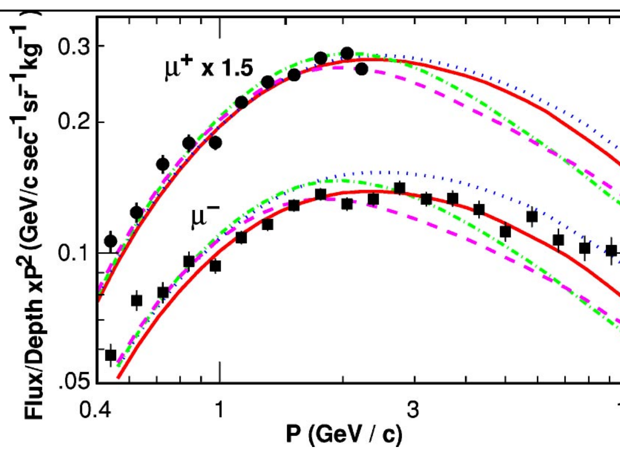
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

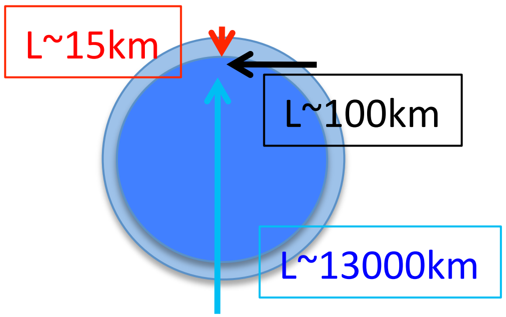
Detailed calculations has been carried out

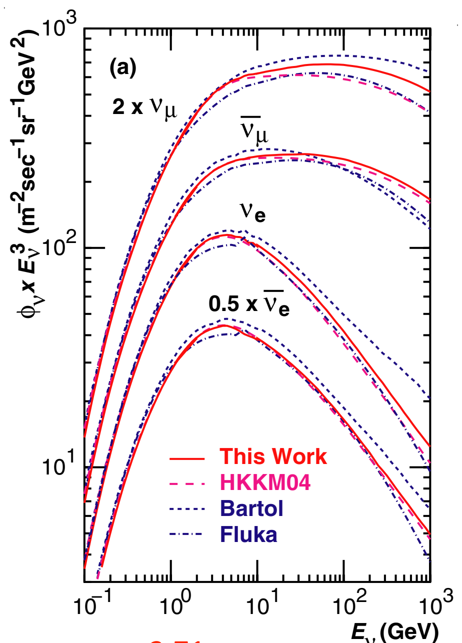
- Primary CR fluxes
- p+A cross section, π,K yields
- Geomagnetic effect, are taken into account

Cosmic Ray Muon flux (Data/Calculation)

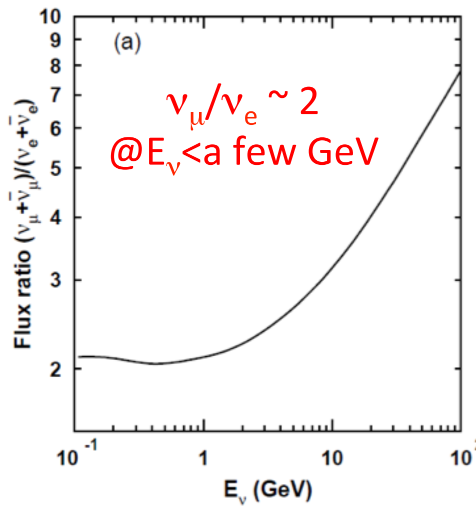


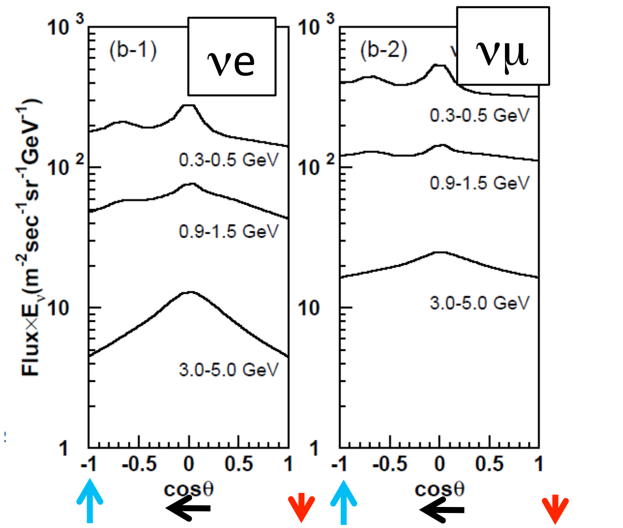
Atmospheric neutrinos (cont'd)



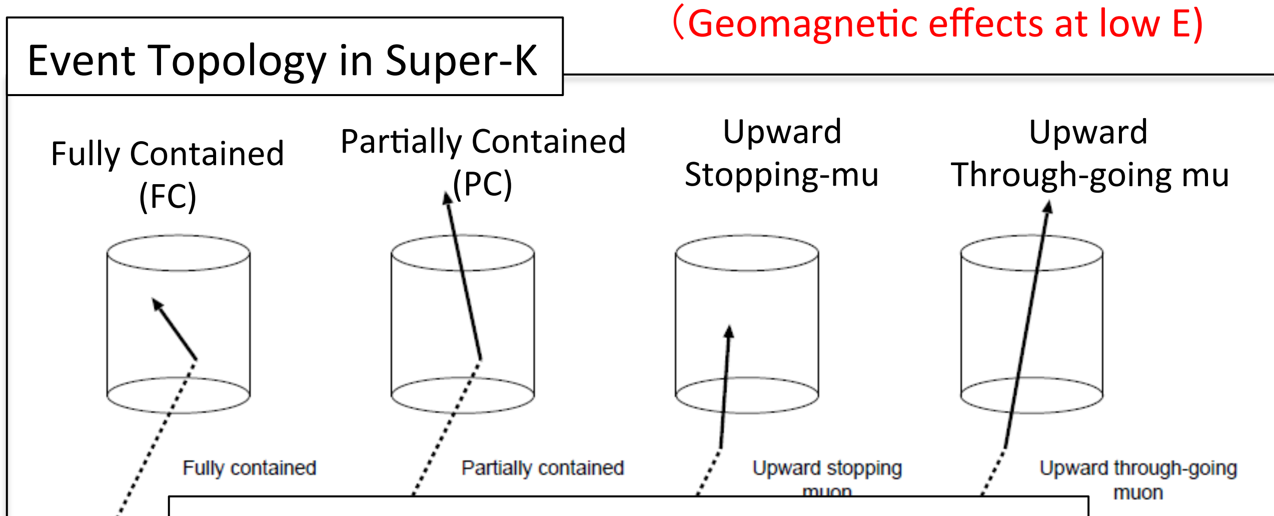


Flux ~ $E^{-2.71}$ at high energy region, <10% uncertainty @ 1GeV region





Up-down symmetric E_ν > a few GeV
(Geomagnetic effects at low E)



~100MeV – over TeV neutrinos are observed

Neutrino Interactions

Dominant interaction at this energy range is neutrino interactions on nucleons

- Charged Current (CC) interactions

  ex.) CC quasi–elastic scattering (CCQE)

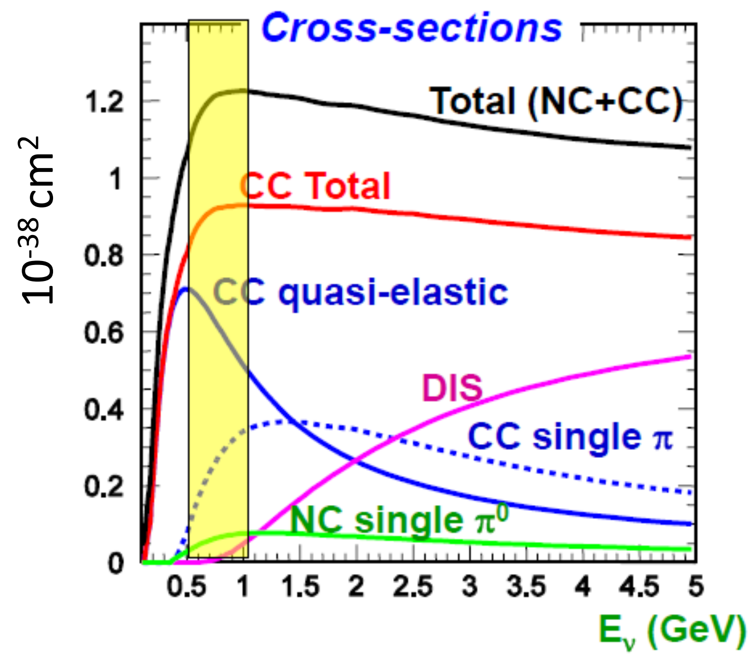
  $$\nu_e + n \rightarrow e^- + p$$
  $$\nu_\mu + n \rightarrow \mu^- + p$$

  Identify the neutrino species by charged lepton

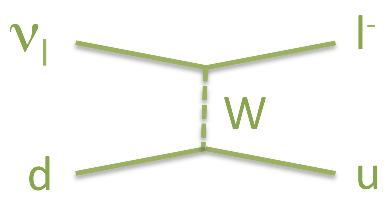
- Neutral Current (NC) interactions

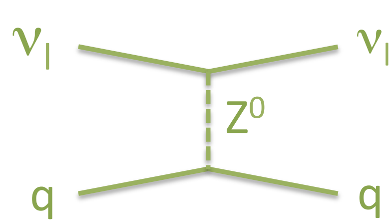
  ex.) NC pion production via baryon resonance

  $$\nu + p \rightarrow \nu + \Delta \rightarrow \nu + N + \pi$$

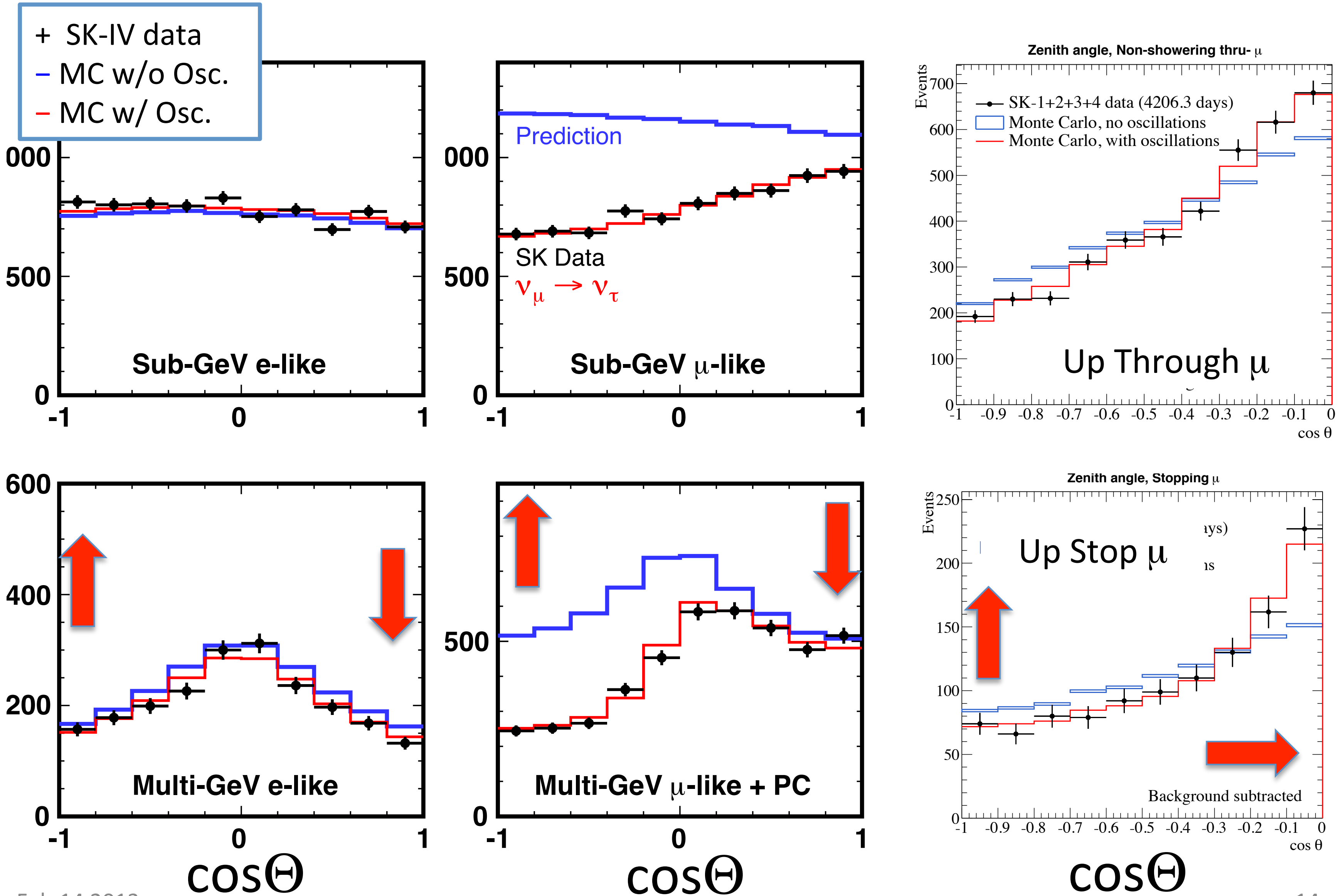


- Hadron production channel cannot be neglected above E~1GeV.
- We adopt a model, NEUT
- Intensive work on modeling of the interaction are on-going based on available modes & data (MiniBooNE, electron scattering, etc.)





Zenith Angle Distributions in SK-IV preliminary

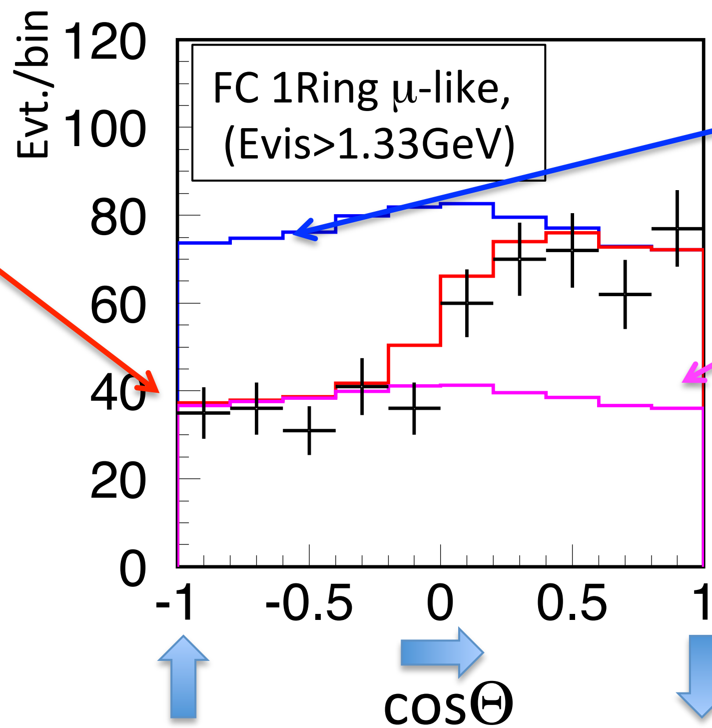


How we extract neutrino oscillation parameters from atmospheric neutrino data?

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L(km)}{E(GeV)}\right)$$

Probability will be averaged to :

$$P(\nu_\mu \to \nu_\mu) \to 1 - \frac{1}{2}\sin^2 2\theta$$



- $\Delta m^2=0$
- $\Delta m^2=2.4\text{x}10^{-3}\text{eV}^2$
- $\Delta m^2=2.4\text{x}10^{-1}\text{eV}^2$

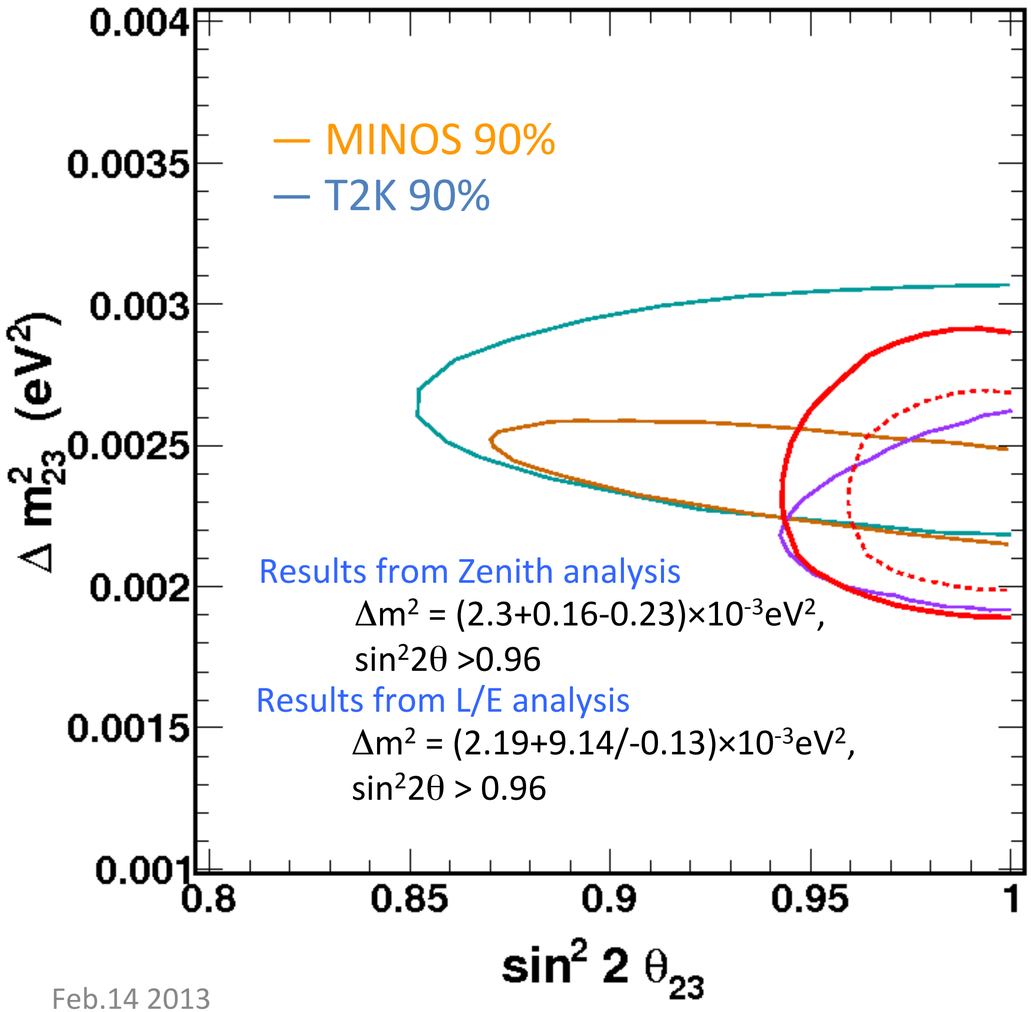
Too small Δm^2 doesn't explain upward deficit

Too large Δm^2 doesn't match with downward data

A band of Δm^2 is allowed

Results ($\nu_\mu - \nu_\tau$ 2 flavor)

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(1.27 \cdot \Delta m_{32}^2 \cdot \frac{L(km)}{E(GeV)}\right)$$



SK-I+II+III+IV (220kton) Zenith angle dist. analysis, Preliminary

— 90% ---- 68% CL

— SK-I+II+III L/E 90%

- Result is consistent with full mixing.
- Atmospheric neutrino analyses shows tightest limit on θ_{23}.
- Long baseline accelerator based ν beam experiments show good agreement with atm.ν results.

3-flavor neutrino oscillation

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2(r\cdot c_{23}^2 - 1) - r\cdot\tilde{s}_{13}\cdot\tilde{c}_{13}^2\cdot\sin 2\vartheta_{23}(\cos\delta_{CP}\cdot R_2 - \sin\delta_{CP}\cdot I_2) + 2\tilde{s}_{13}^2(r\cdot s_{23}^2 - 1)$$

LMA

interference

ϑ_{13} resonance

Full 3-flavor neutrino oscillation probability includes terms driven by θ_{12}, θ_{13}, and interference term. CP violating term, resonant effect from mass effects exist.

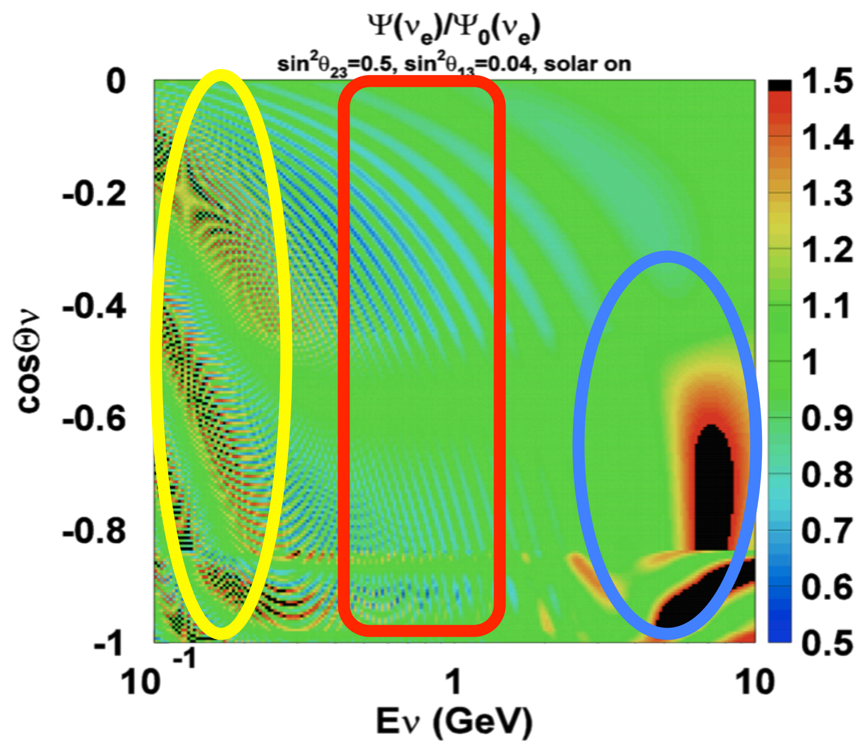
$P_2 = \sin^2 2\theta_{12,M} \sin^2(\phi_m/2)$ where ϕ_m is the phase oscillation in matter

$r = \nu_\mu / \nu_e$ flux ratio as a function of energy

$R_2 = -\sin 2\theta_{12,M} \cos 2\theta_{12,M} \sin^2(\phi_m/2)$

$I_2 = (-1/2) \sin 2\theta_{12,M} \sin\phi_m$

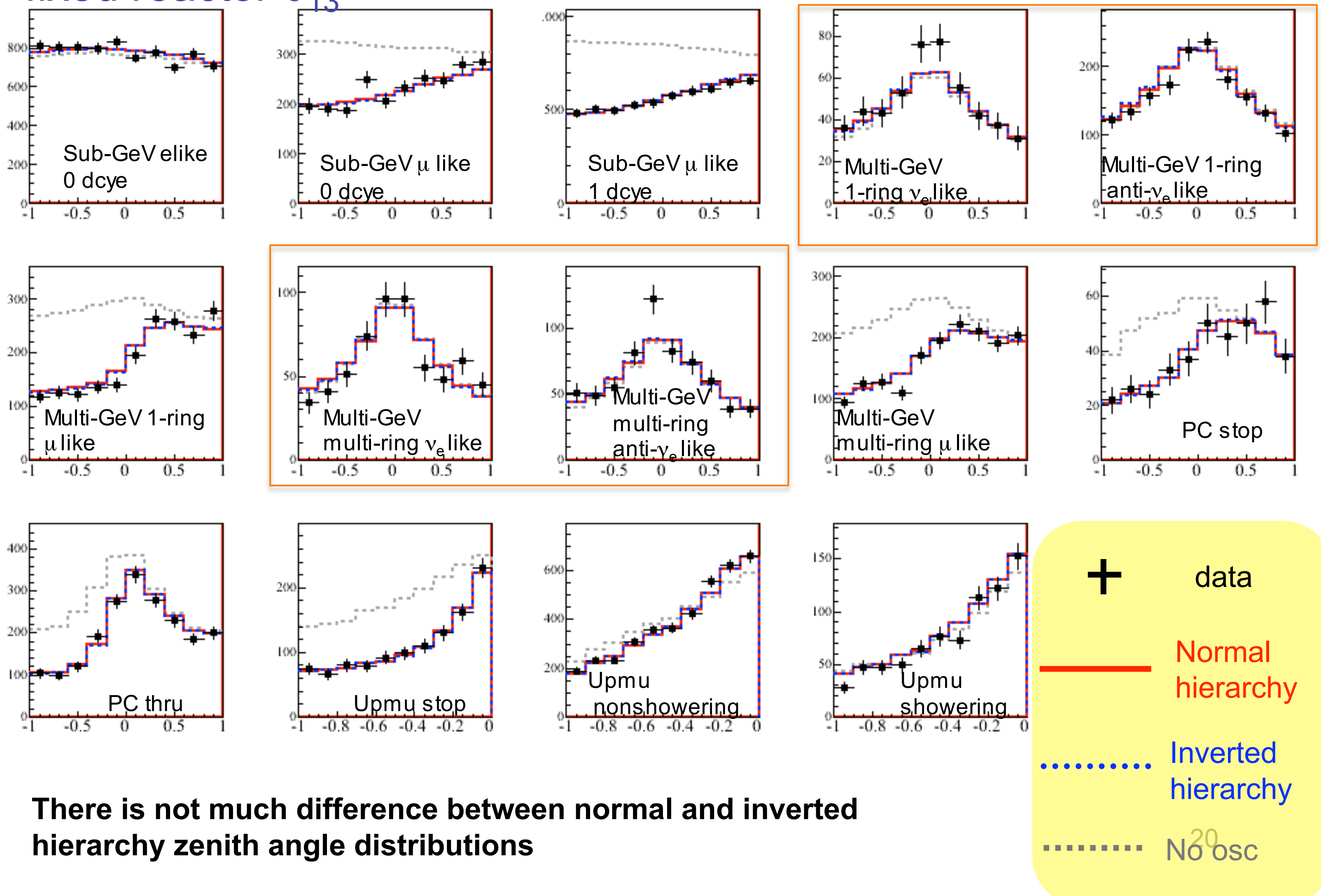
$\tilde{\theta}_{13} \approx \theta_{13,M}$



- Normal mass hierarchy
  → resonance effect on ν_e
- Inverted mass hierarchy
  → resonance effect on anti-ν_e

SK1 + SK2 + SK3 + SK4 (Normal and Inverted hierarchy)

*fixed reactor θ_{13}

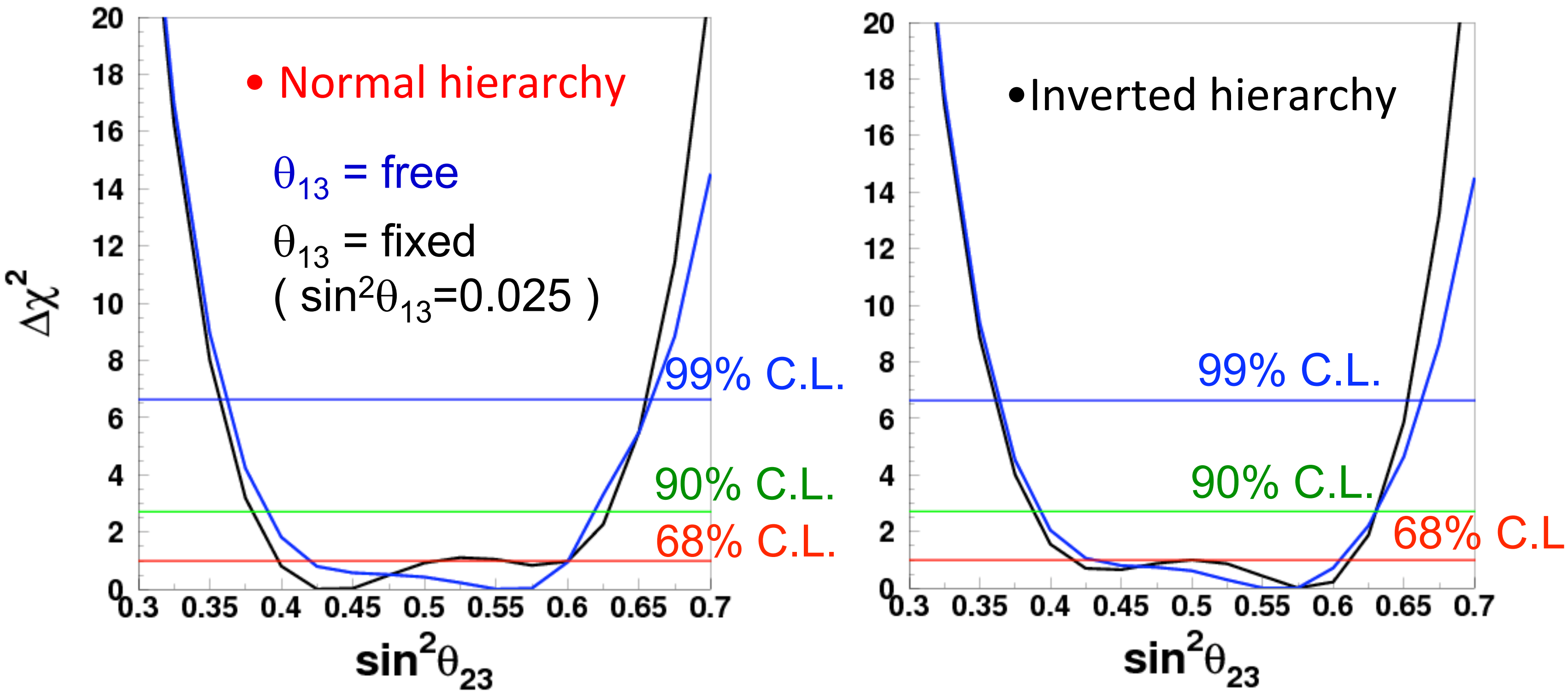


There is not much difference between normal and inverted hierarchy zenith angle distributions

ν_e enriched sample/ anti-ν_e enriched samples are used to increase sensitivity.

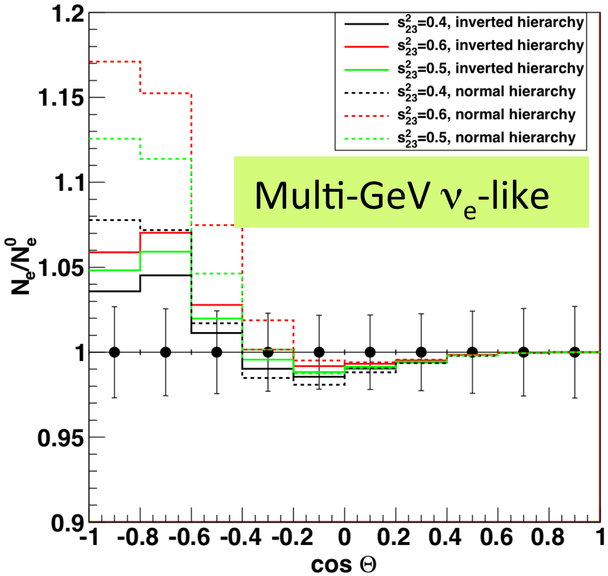
Mass hierarchy

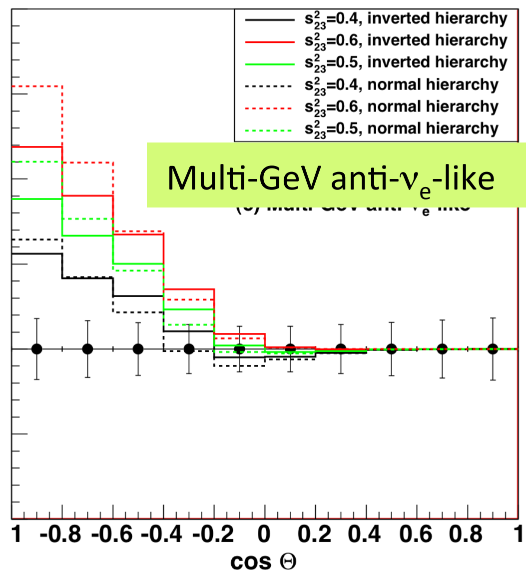
Normal hierarchy (NH):χ^2_{min}= 556.7/477dof
Inverted hierarchy (IH):χ^2_{min}= 555.5/477dof
→ $\Delta\chi^2$ = 1.2



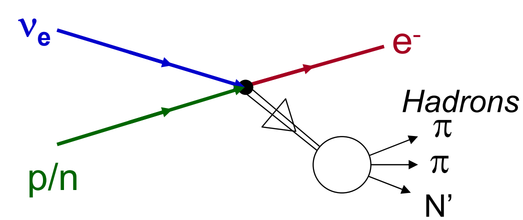
No siginificant difference between normal and inverted hierarchy

Sensitivity to mass hierarchy: Zenith angle distributions for N_e/N^0_e





A separation of neutrino and expected to help to see mass hierarchy.



Larger upward ν_e appearance in normal hierarchy case

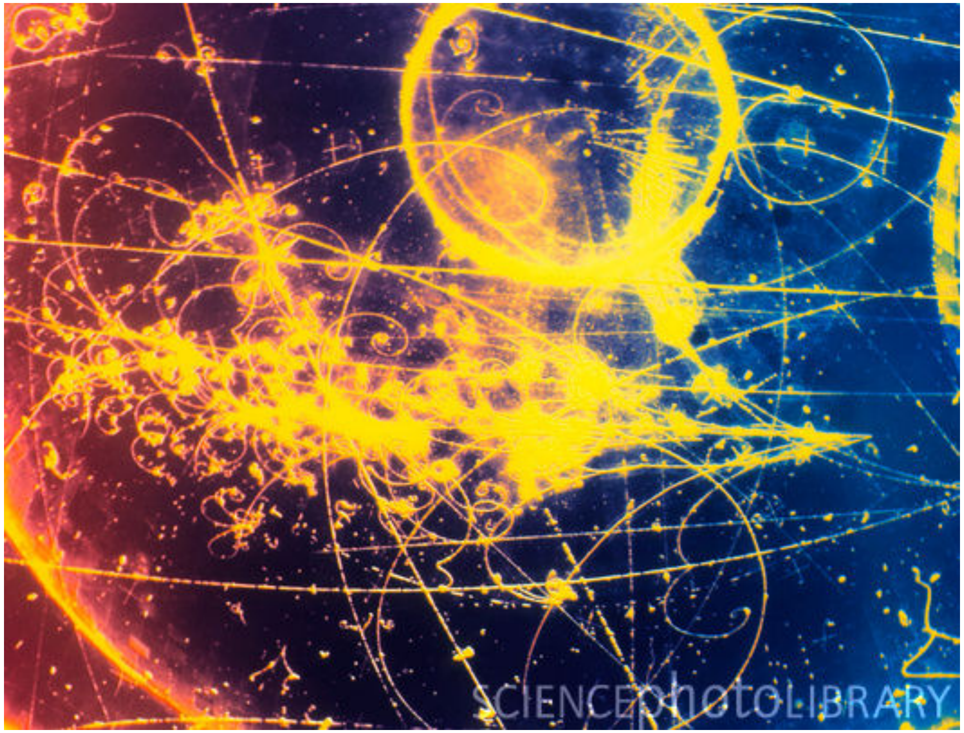
$\sin^2\theta_{23} = 0.4$ — Inverted (solid line)
$\sin^2\theta_{23} = 0.5$
$\sin^2\theta_{23} = 0.6$ — Normal (dotted line)

current enrich technique

Observables	ν_e *CC*	$\bar{\nu}_e$ *CC*
Energy fraction of the most energetic ring	Smaller	Larger
Number of rings	More	Fewer
Transverse momentum	Larger	Smaller
# of decay electrons	More	Fewer
Purity of selected samples	59%	32%

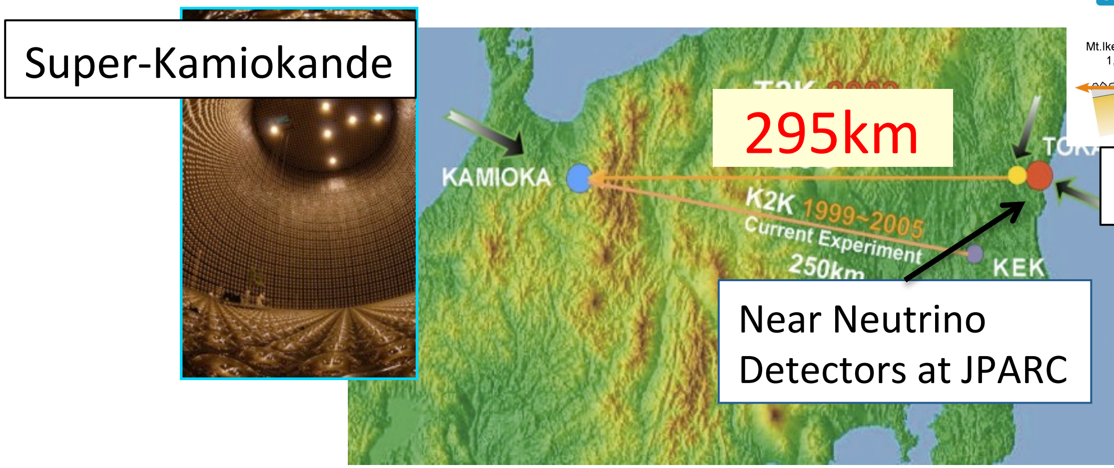
Error bars = Hyper-K 10 year exposure~250 SK year(!) exposure

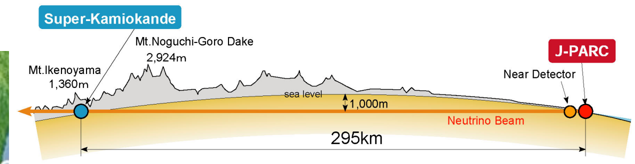
T2K experiment : Beam neutrino based long baseline neutrino oscillation experiment

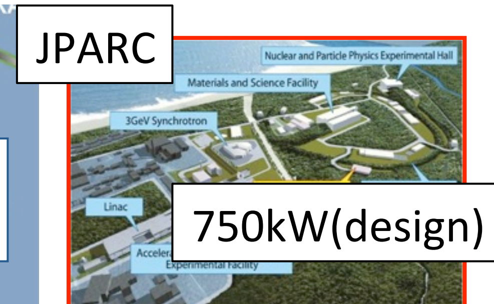


T2K (Tokai to Kamioka) Long Baseline Neutrino Oscillation Experiment

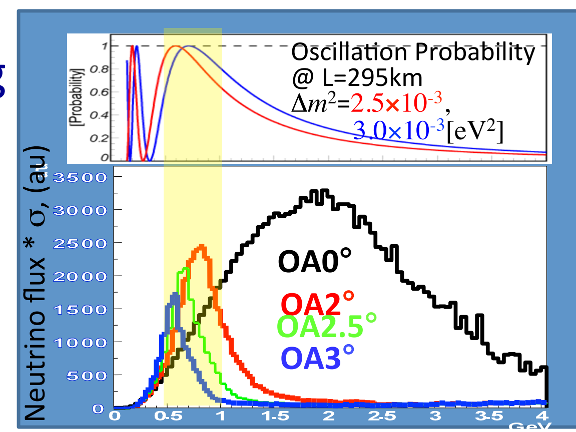
First Long baseline experiment with Intensive off-axis neutrino beam







- Quasi-monochromatic nm beam
- Fast extraction of protons → pulsed ν beam → timing based ν event selection
- Precise measurement of ν beam at near site (ND280)



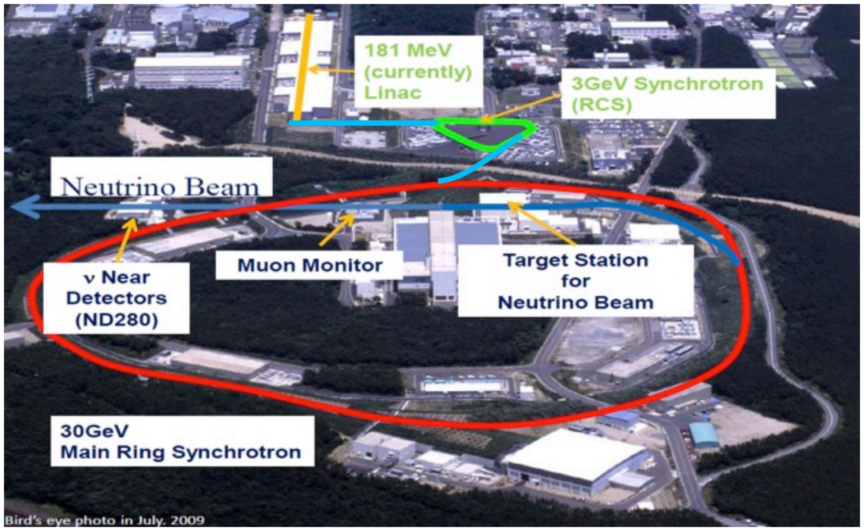
Off Axis = 2.5° is selected.

Physics Goals:

- Discovery of ν_μ → ν_e appearance
- Precise measurement of ν_μ disappearance

$\delta(\Delta m^2_{23}) \sim 1\text{x}10^{-4}$ eV^2 , $\delta(\sin^2 2\theta_{23}) \sim 0.01$

Experimental Setup:
J-PARC Accelerator and Experimental Facility

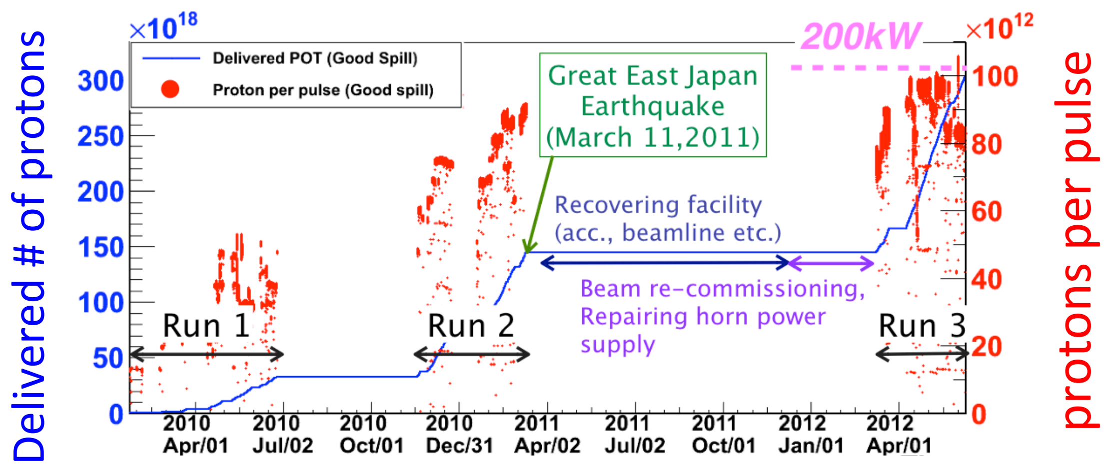


- 30GeV Proton synchrotron
- 6 bunch (before Autumn 2010)
- 8 bunch (2010 Autumn -)

- 581ns interval
- ~ 0.3 Hz repetition rate
- Construction finished 2008 JFY

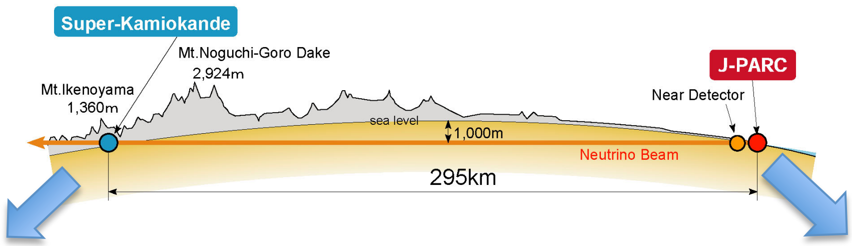
Fast Extraction
→ pulsed neutrino beam

- Accelerator facility, beam monitors, neutrino detectors are stably running
- Now we accumulate up to 3.0E20 P.O.T.



How to select T2K beam neutrino event at Super-Kamiokande

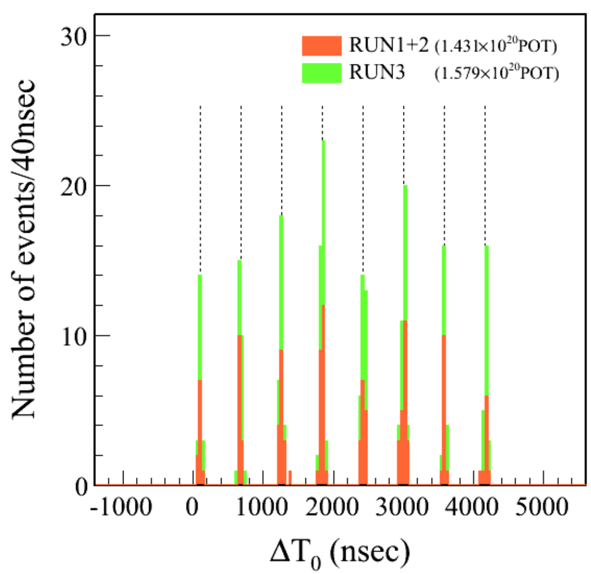
- Select PMT signals in a interval (1ms) at expected arrival time of beam neutrinos.

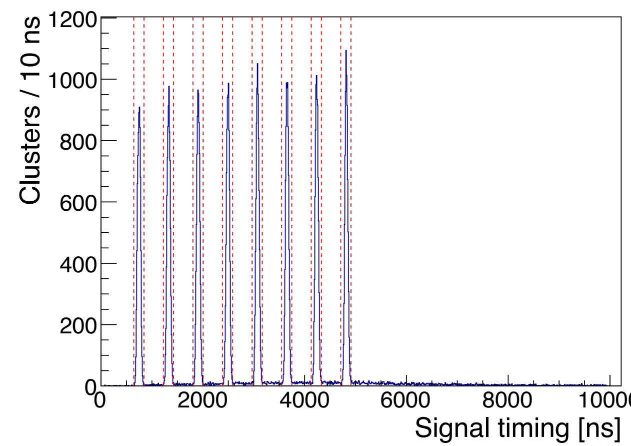


Observed SK event timing
(relative to beam arrival time)

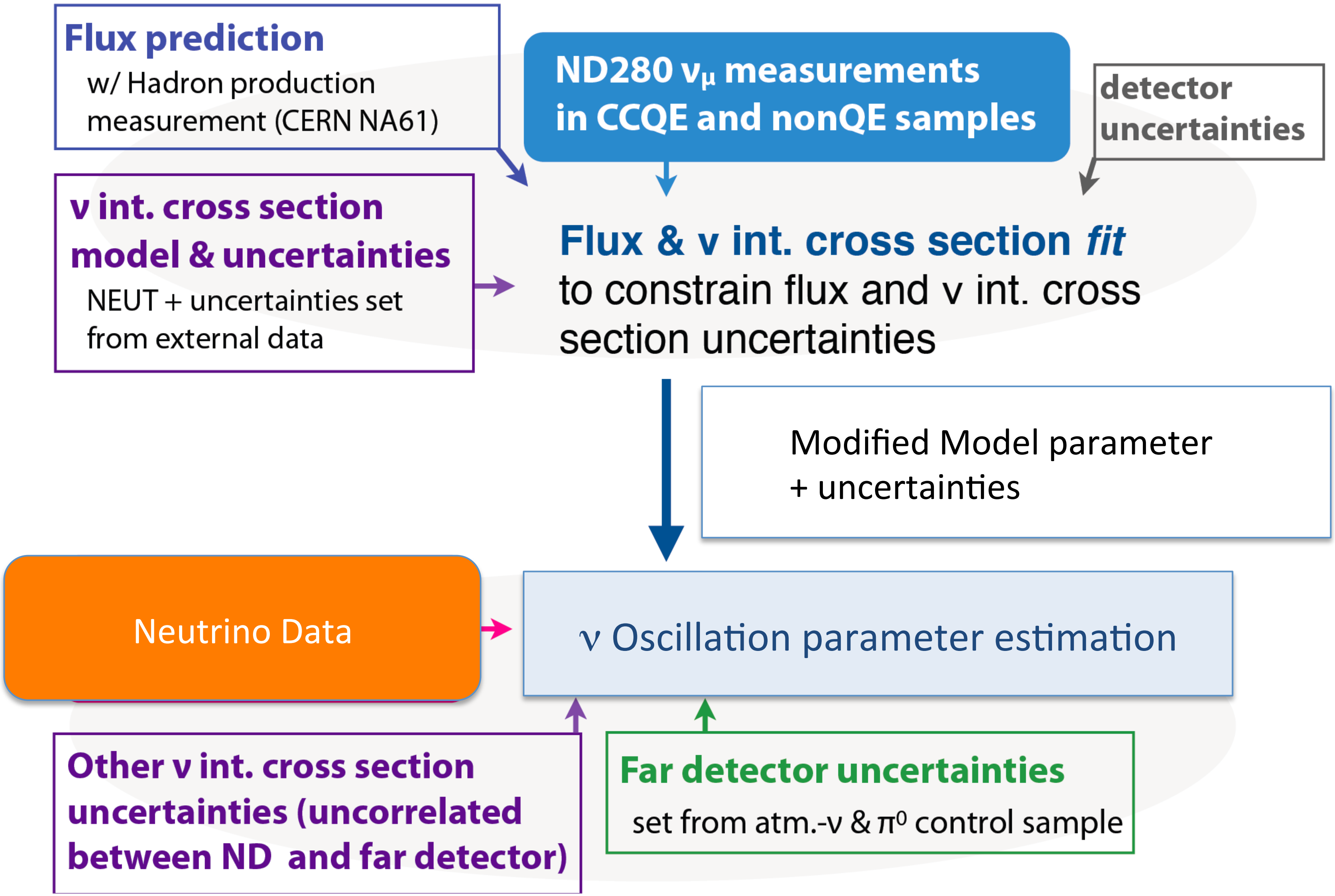
Accelerator issues time stamp to ND280, and to Super-K delivered via Network

Observed ND280 event timing
(relative to beam time)





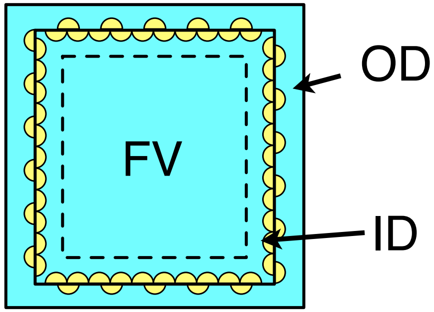
Analysis Schemes



ν_e appearance

($\nu_\mu \rightarrow \nu_e$ oscillation)

ν_e event selection at Super-Kamiokande

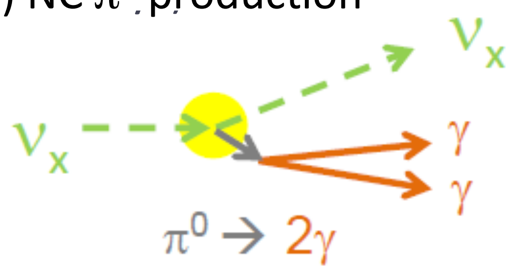


CCQE ν_e interaction enriched sample are selected to find $\nu_\mu \rightarrow \nu_e$ signal

Signal : CC interaction of ν_e

Backgrounds

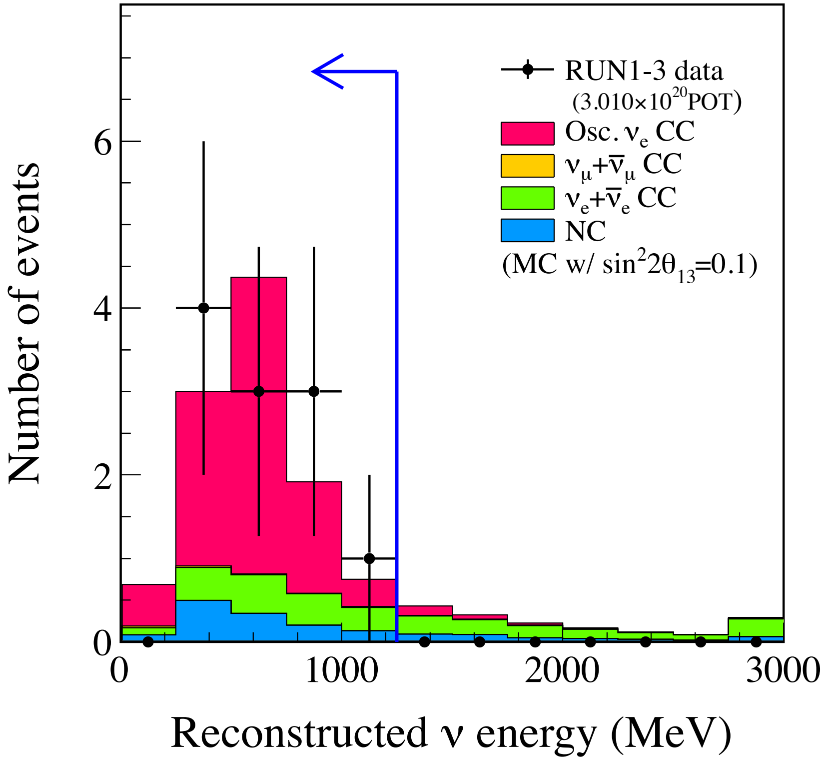
(1) intrinsic ν_e
(2) NC π^0 production



Selection Criteria:

- T2K beam timing & Fully-contained（FC）
- in fiducial volume（FV）
  - ✓ Reject events induced outside of ID
  - ✓ Keep performance of event reconstruction
- 1 Cherenkov ring, electron-like
- Visible Energy >100MeV
  - ✓ Reduce NC background, decay-electrons
- No delayed electron signals
- Remaining p0 rejection with special algorithm.
- Reconstructed n energy < 1250MeV

ν_e candidates (3.0×10^{20}P.O.T. data)



11 events are observed

(expected B.G.: 3.22 ± 0.43 events)

High background rejection power.

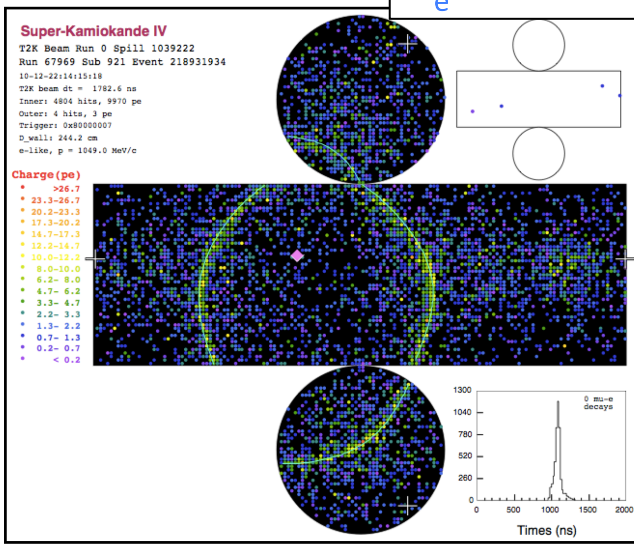
Rejecting

- 99.9% ν_μCC
- 77% beam ν_eCC
- 99% NC

High Efficiency

- ν_eCC 66% are remained

ν_e candidate events



Preliminary

Significance of the observation

ν_e candidate events (3.01x10^{20} p.o.t.) :

Observed : 11 events

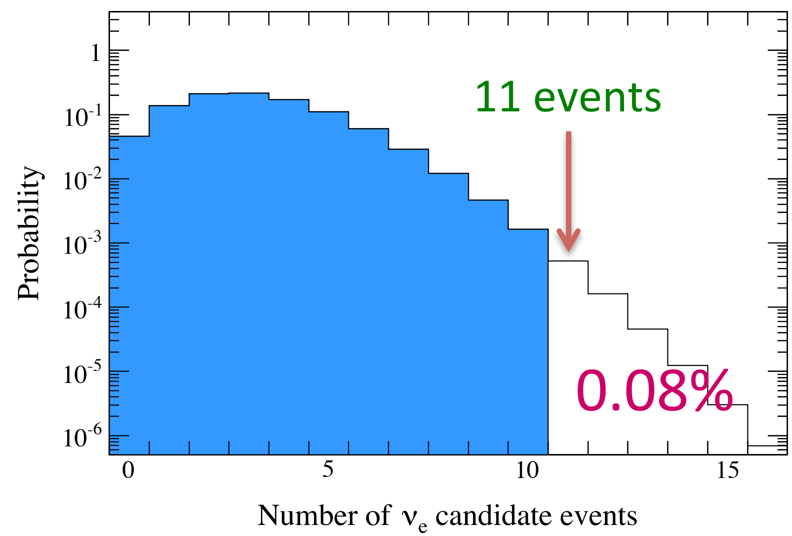
Expected w/ $\sin^2 2\theta_{13}=0$: 3.22 ± 0.43 events

Probability that 11events observed for $\sin^2 2\theta_{13}=0$ = 0.08%.

→ 3.2σ significance

Evidence of ν_e appearance !

Number of ν_e candidate events over 1x10^8 toy MCs w/ $\theta_{13}=0$



Preliminary

Results (with spectrum)

Best fit with 1σ errors

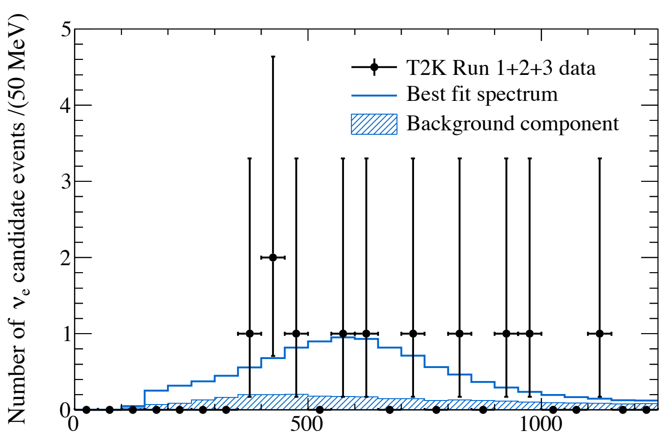
Normal hierarchy

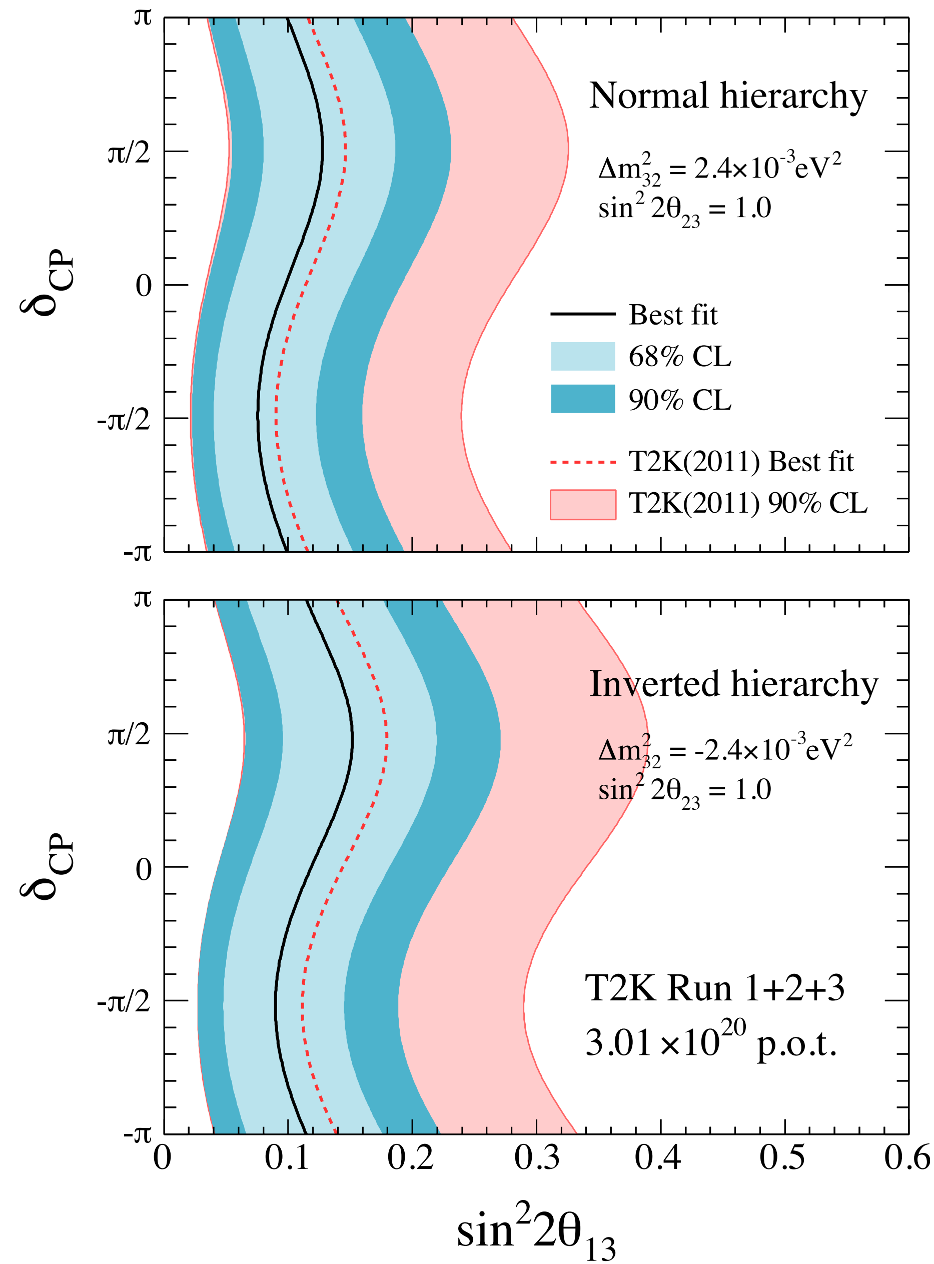
$$\sin^2 2\theta_{13} = 0.098\,^{+0.052}_{-0.042}$$

Inverted hierarchy

$$\sin^2 2\theta_{13} = 0.118\,^{+0.063}_{-0.049}$$

for δ_{CP}=0, $\sin^2\theta_{23}$=0.5

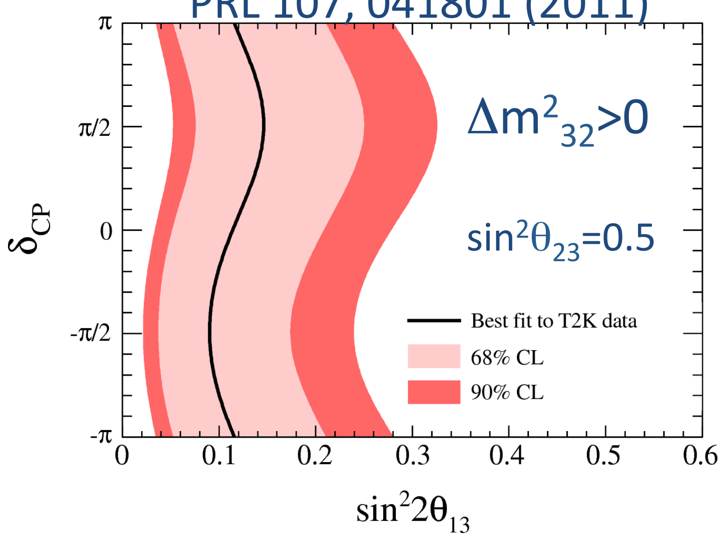




Breakthrough of non-zero θ_{13} search (2011~)

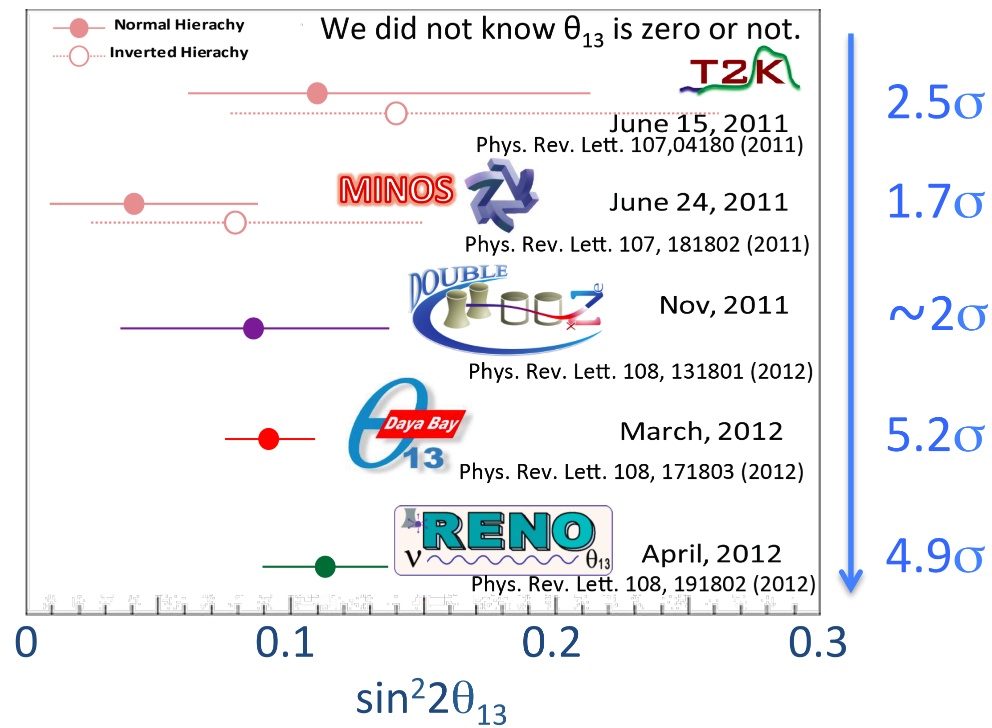
- In 2011 June, T2K reported the first indication of $\theta_{13}\neq0$ (2.5σ)using the data before the earthquake.

PRL 107, 041801 (2011)



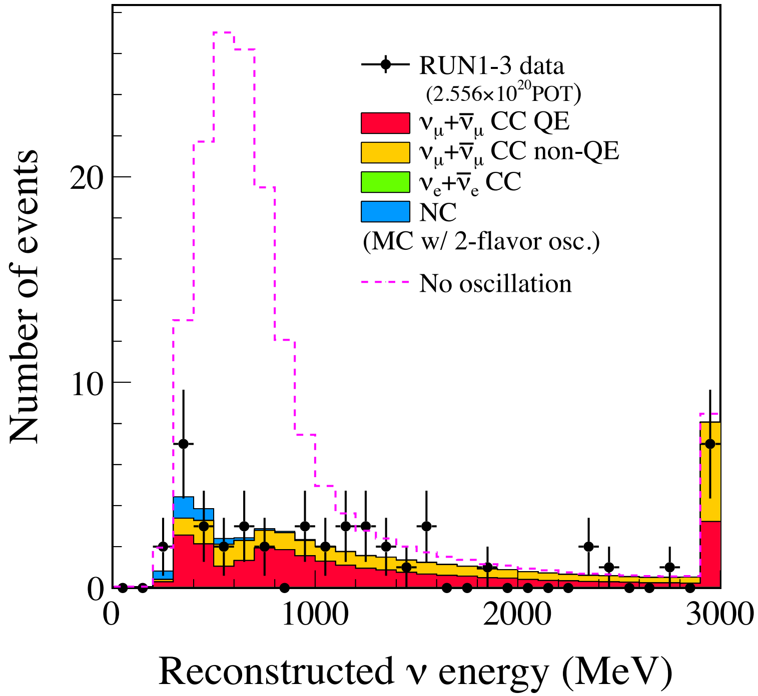
- A solid confirmation of $\theta_{13}\neq0$ had been given by reactor neutrino experiments.

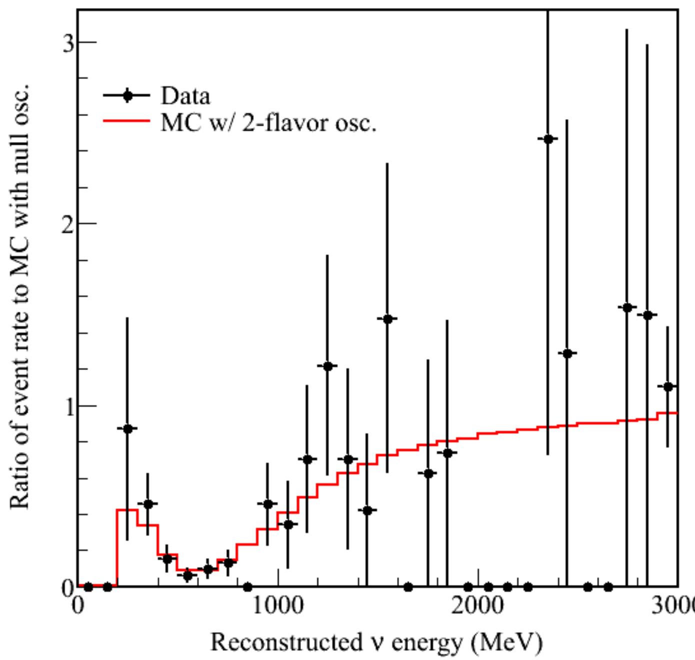
1σ confidence intervals (before Neutrino2012)



ν_μ disappearance
($\nu_\mu \rightarrow \nu_x$ oscillation)

CCQE ν_μ interaction enriched sample are selected to see the energy spectrum skew of ν_μ

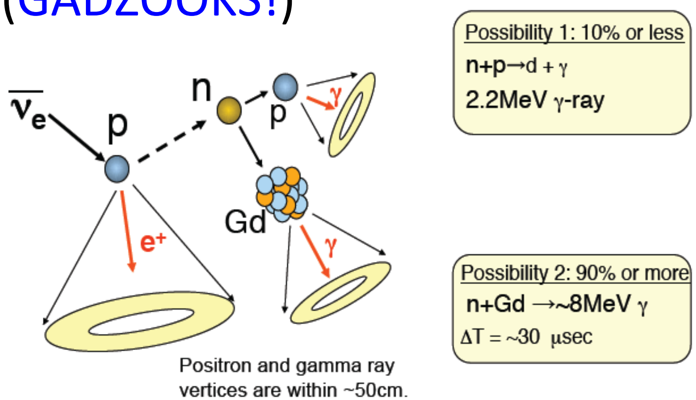




- Analysis with Run 1+2+3 (3.01E20POT) is on going.
- Run 1+2 (1.43E20POT) was published.

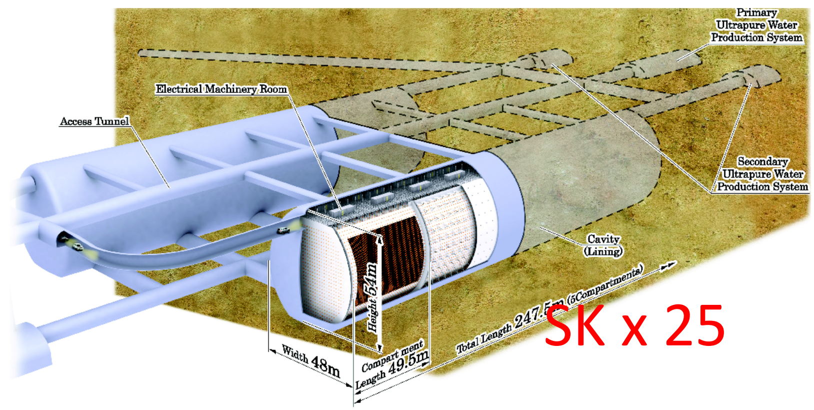
Future prospect in Kamioka

Super-K with Gd doped Water
(GADZOOKS!)

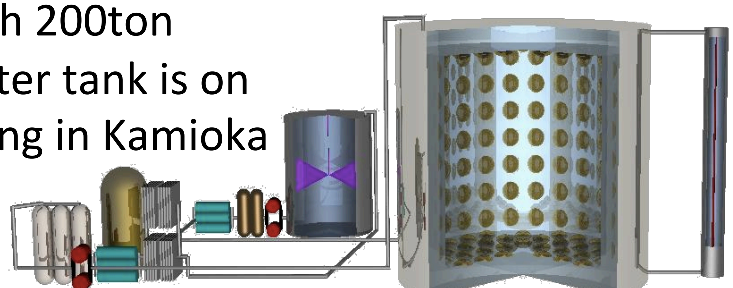


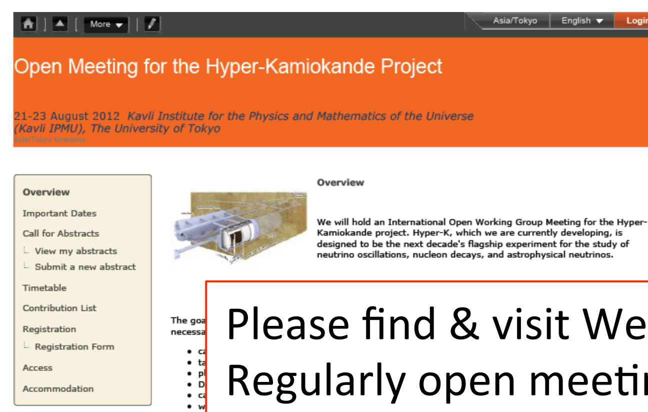
anti-ν_e can be identified by the delayed coincidence technique

Kamioka 3rd Generation
1Mt Water Cherenkov Detector
(Hyper-Kamiokande Project)



Technical R&D with 200ton water tank is on going in Kamioka





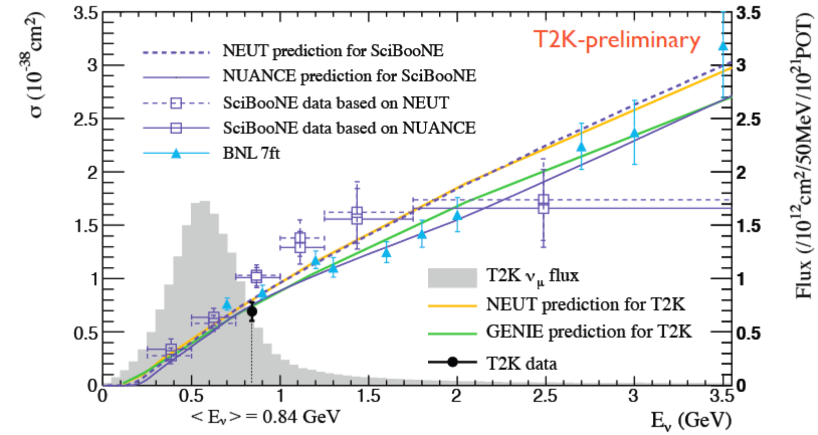
Please find & visit Web page
Regularly open meetings are held

Summary

- Super-Kamiokande is world-wide largest Water Cherenkov detector. Multi physics targets are covered.
- Neutrino oscillation is discovered in 1996, and after next decade, the situation drastically progressed.
- We now know non-zero 3 mixing angles, and two mass differences. Mass hierarchy, CP violation.
- Atmospheric neutrino still gives stringent limit on θ_{23}. Can access to mass hierarchy with matter effect in the Earth. Still need improved analyses and improved statistics.
- T2K experiment now have evidence of ν_e appearance with 3.2σ significance. Appearance opens a channel to CP phase, and establish of the appearance channel is very important to next neutrino physics.

Other studies in T2K

- Cross section measurements
  - Preliminary results from the flux averaged ν_μCC inclusive cross section measurement



- Nuclear g-rays from de-excitation of residual nuclei (^{15}O, ^{16}N,..) induced by Neutral Current scattering of ν.

ex.) $\nu + ^{16}O \rightarrow \nu + p + ^{15}O^* \rightarrow \gamma(6MeV)$ + residuals.

- Sterile neutrino search at T2K using NC nuclear de-excitation γ-rays
  - Preliminary results w/ Run1+2 data

and more …