Recent results from Super-Kamiokande and T2K

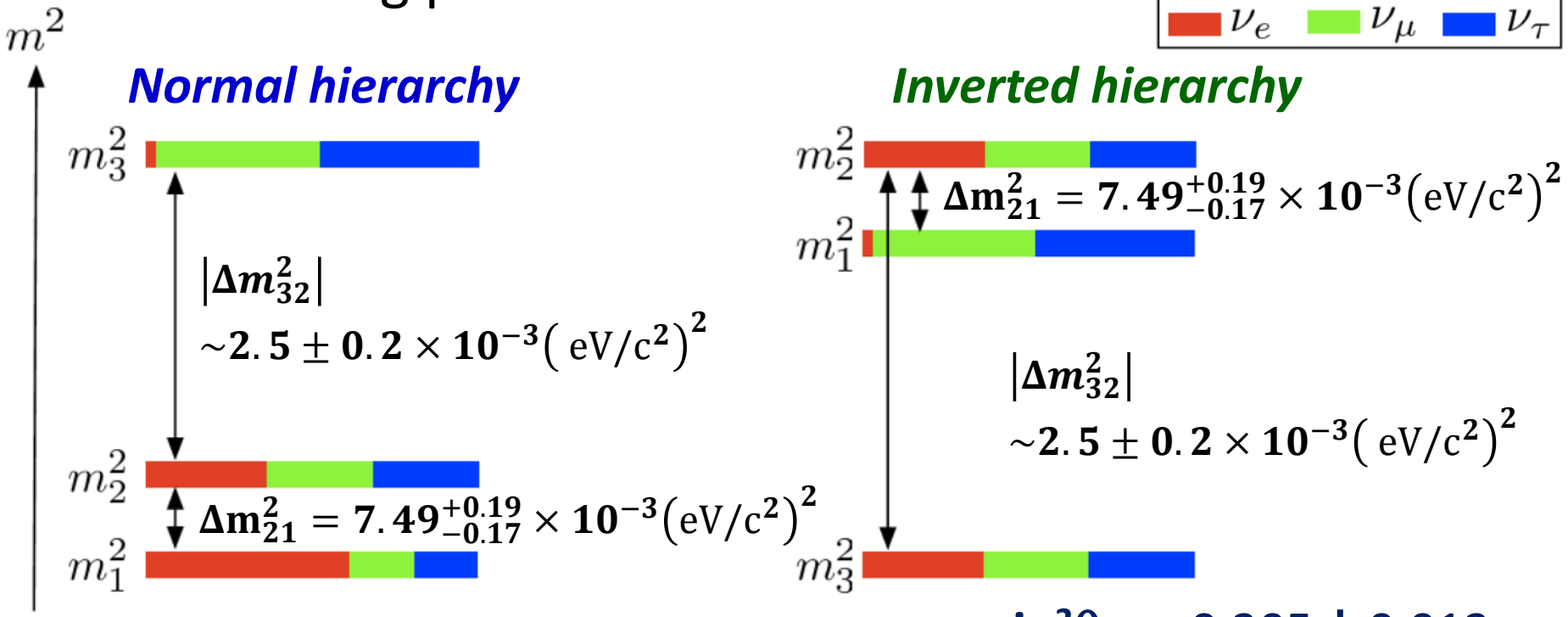
~ atmospheric and accelerator neutrinos ~

Yoshinari Hayato (Kamioka, ICRR and Kavli IPMU, U-Tokyo)

for the Super-Kamiokande collaboration

and the T2K collaboration

Neutrino mixing parameter measurements



$\sin^2\theta_{12} \sim 0.305 \pm 0.013$

$\sin^2 2\theta_{13} = 0.098 \pm 0.013$

Remaining questions

1) θ_{23} is really 45° or < 45° or >45° ?

Current uncertainty of $\sin^2\theta_{23}$ is still large ~ 10% level

$\sin^2\theta_{23} = 0.514 \pm 0.055$ **(T2K 2014)**

2) CP is violated or not (δ = 0 or not) ?

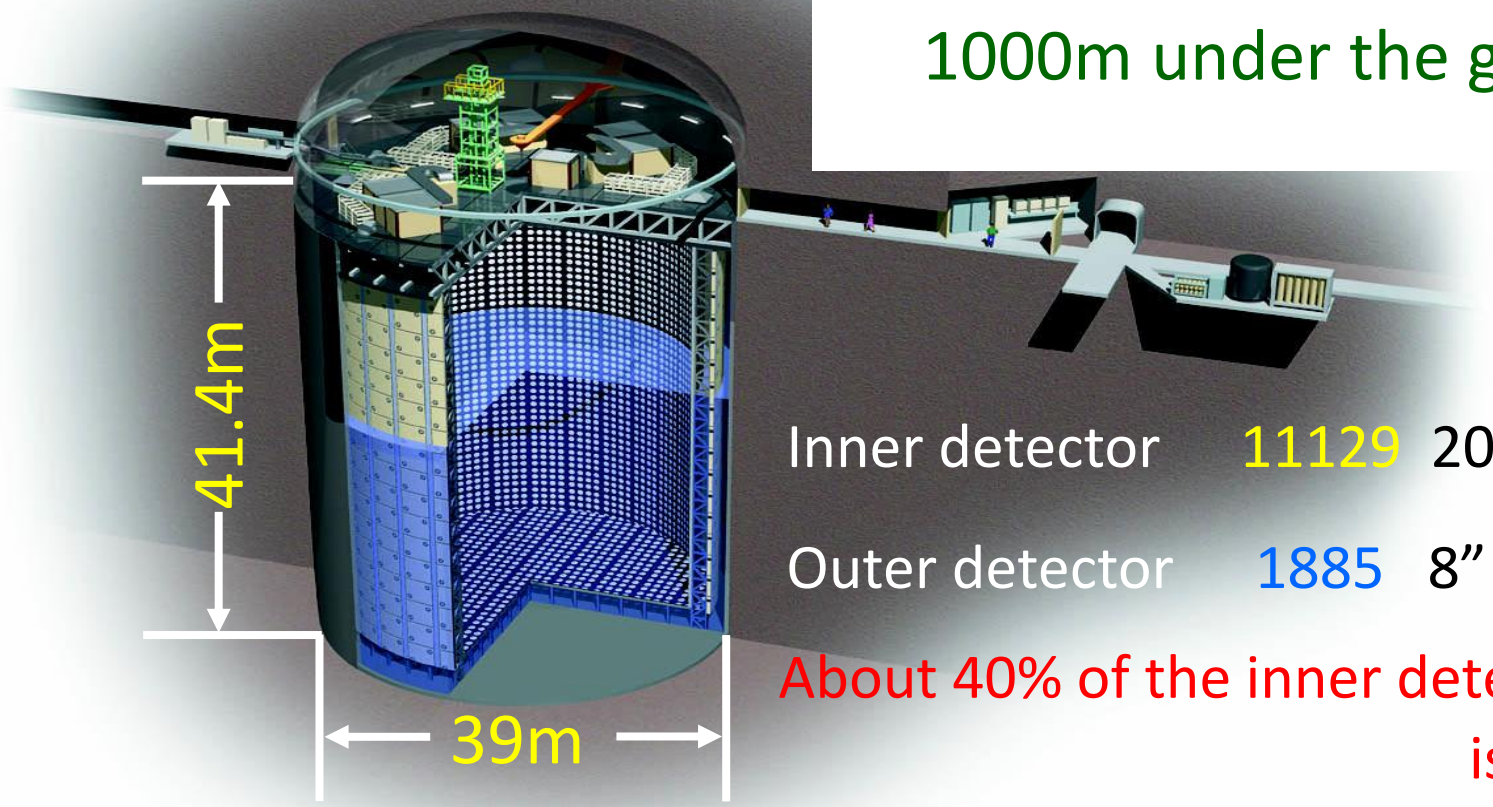
3) Mass hierarchy ~ which is heavier ? ($\Delta m^2_{32} > 0$ or < 0 ?)

Super-Kamiokande

50000 tons Ring imaging Water Cherenkov detector

Fiducial volume : 22.5 ktons

1000m under the ground



Inner detector 11129 20” PMTs

Outer detector 1885 8” PMTs

About 40% of the inner detector is covered by the sensitive area of PMT.

Operation started in Apr. 1996.

Physics in Super-Kamiokande

Neutrino oscillation

- Accelerator neutrinos
- Atmospheric neutrinos
- Solar neutrinos

GUT

Proton decay

$p \rightarrow e^+ + \pi^0$

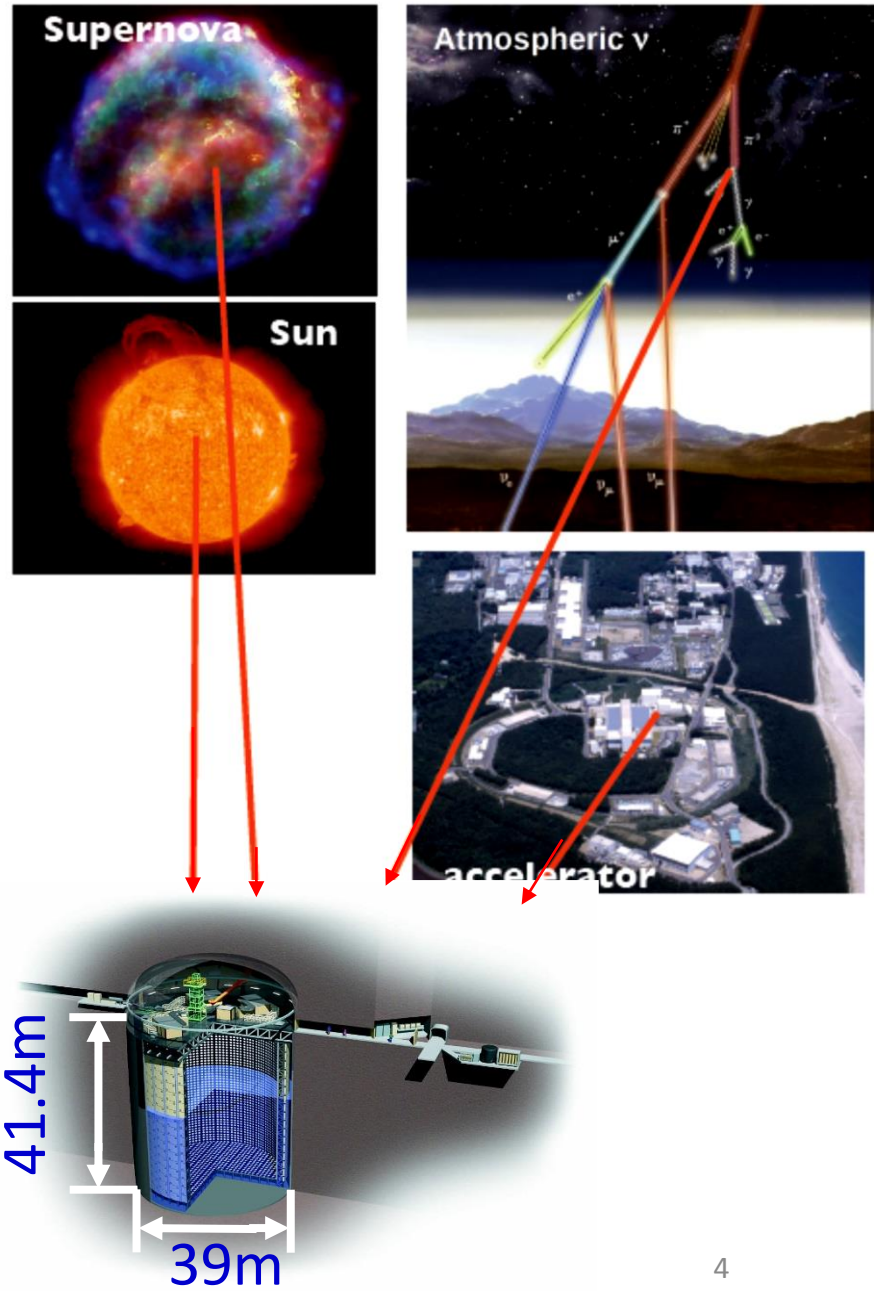
$p \rightarrow K^+ + \bar{\nu}$

New physics

- WIMP search
- n-$\bar{n}$ oscillation
- dinucleon decay etc….

Neutrino astrophysics

- Supernova burst neutrino
- Supernova relic neutrino



Super-Kamiokande detector

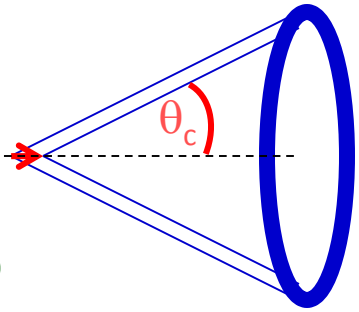
Ring imaging water Cherenkov detector

Cherenkov light

emission : if $n \cdot \beta > 1$

n : refractive index

$\beta = p / E$



direction : $\cos\theta_c = 1/(n \cdot \beta)$

$n_{water} \sim 1.33$ ➡ $\theta_c \sim 42$ degree.

of emitted Cherenkov photons

➡ ~ 340 photons / 1cm

$$\frac{d^2 N_{photon}}{d\lambda dL} = \frac{2p\alpha Z^2}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right)$$

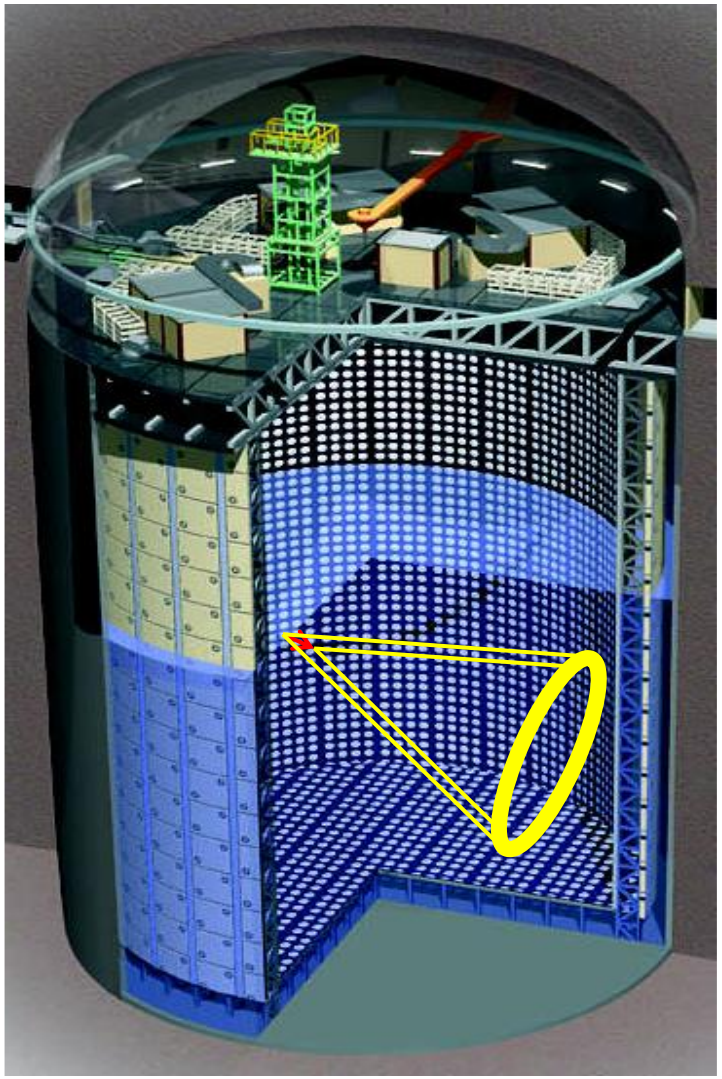
Sensitive wave length of PMT: 300 ~ 600nm

Cherenkov angle θ=42 degree, Z (charge) =1

Detected # of photons used

are much smaller.

PMT quantum efficiencies, PMT coverage, light absorption in the water etc..



Super-Kamiokande detector

Ring imaging water Cherenkov detector

Event reconstruction

Amount of the Cherenkov photons

∝ Momentum of the particle

➡ Use observed # of photons

to reconstruct energy.

Interaction position

~ starting point of the charged particle

➡ Use photon arrival timing.

Ring pattern is also used

for the precise reconstruction.

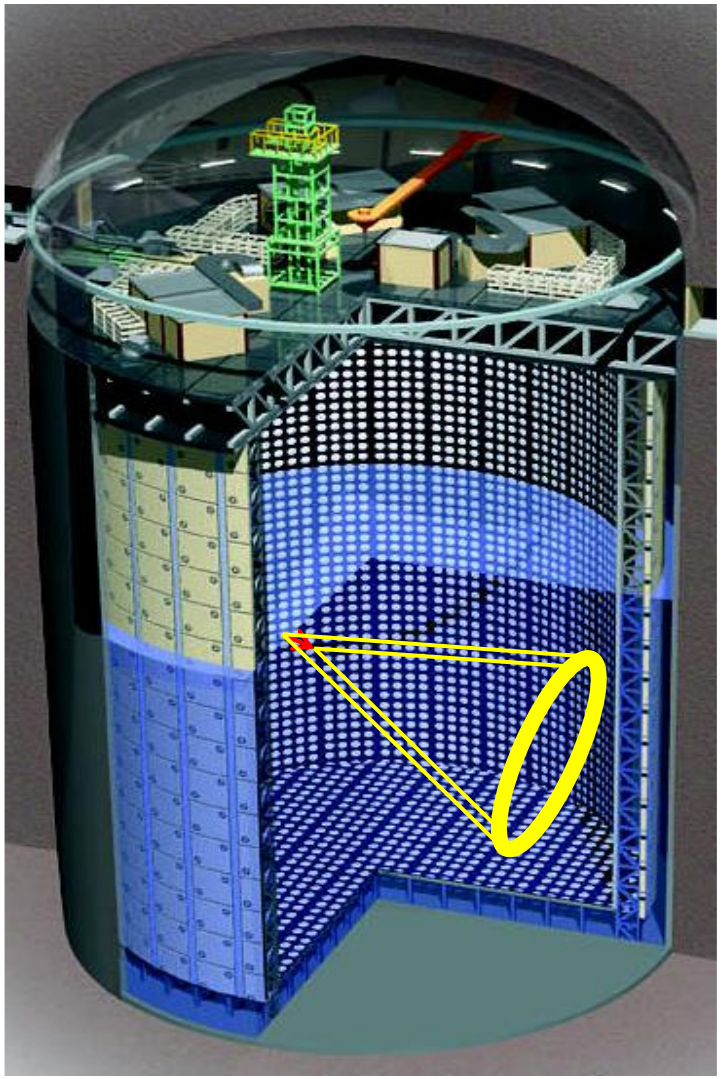
of the charged particles & γ

➡ # of the Cherenkov rings

Also, electrons generated

by the decay of μ, π etc.

gives useful information.



Super-Kamiokande detector

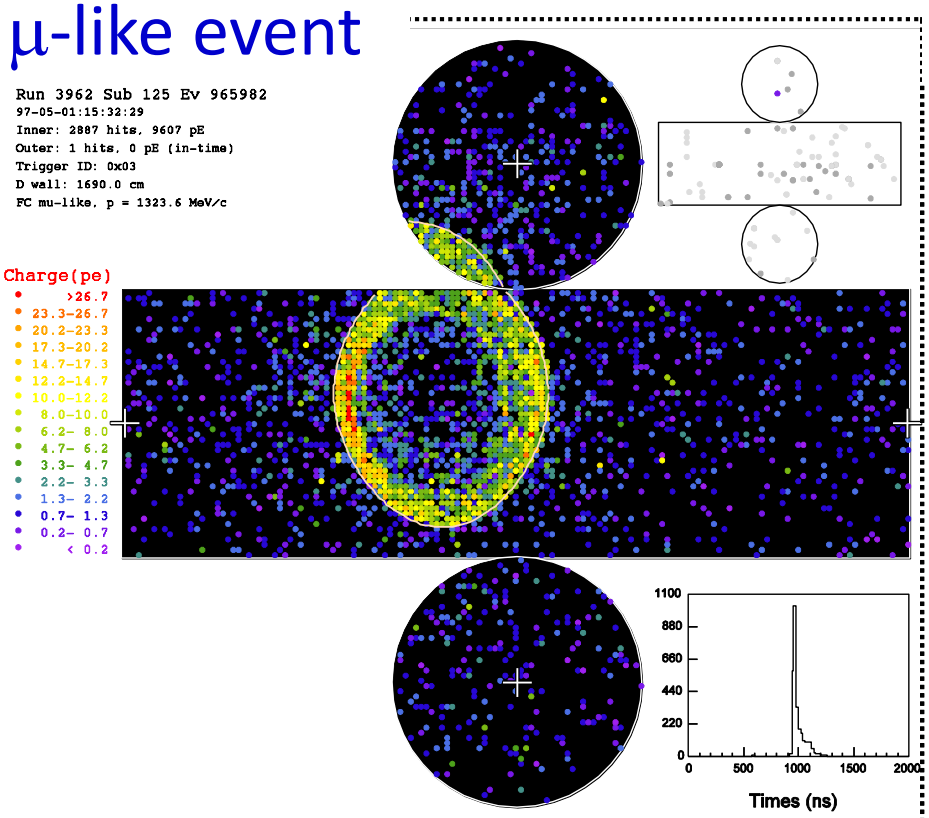
Ring imaging water Cherenkov detector

Pattern of the Cherenkov ring depends on the particle type

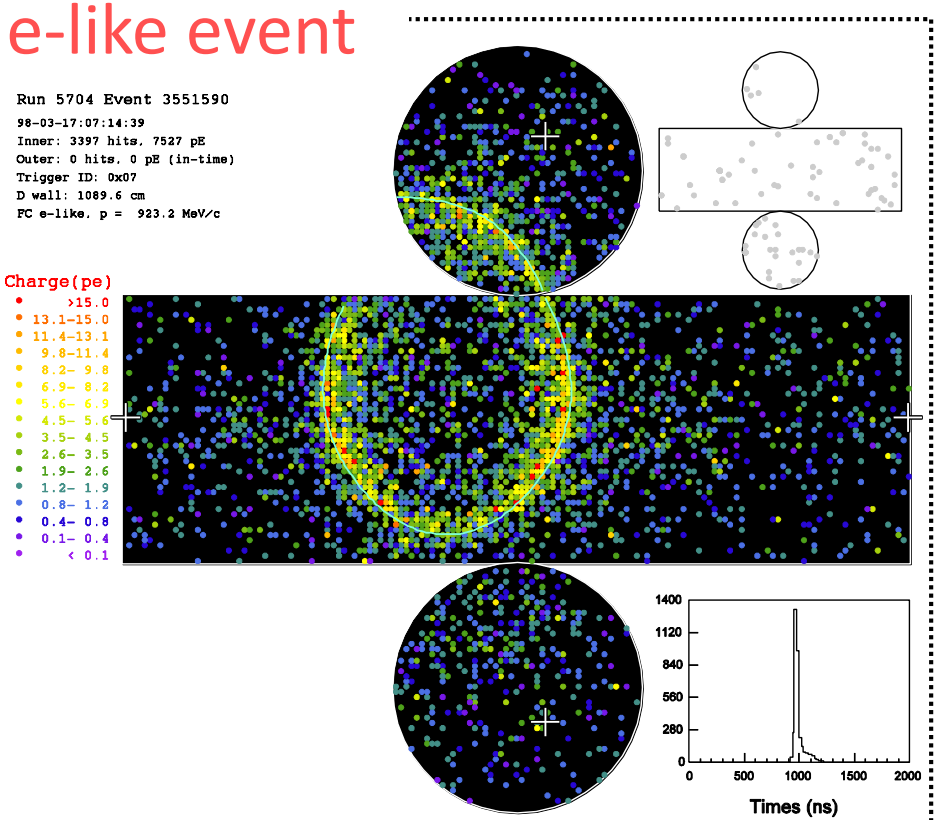
Particle type can be identified using the shape of the ring.

Electron (or gamma) generates electro-magnetic shower and ring is more diffused compared to the muon.

μ-like event

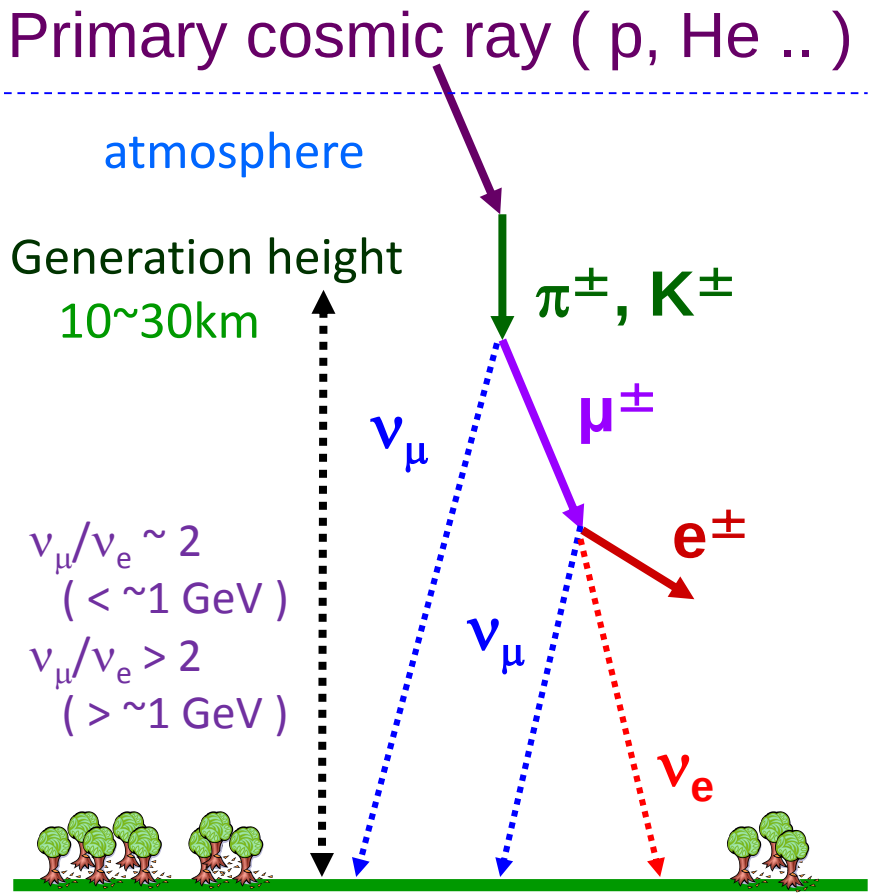


e-like event

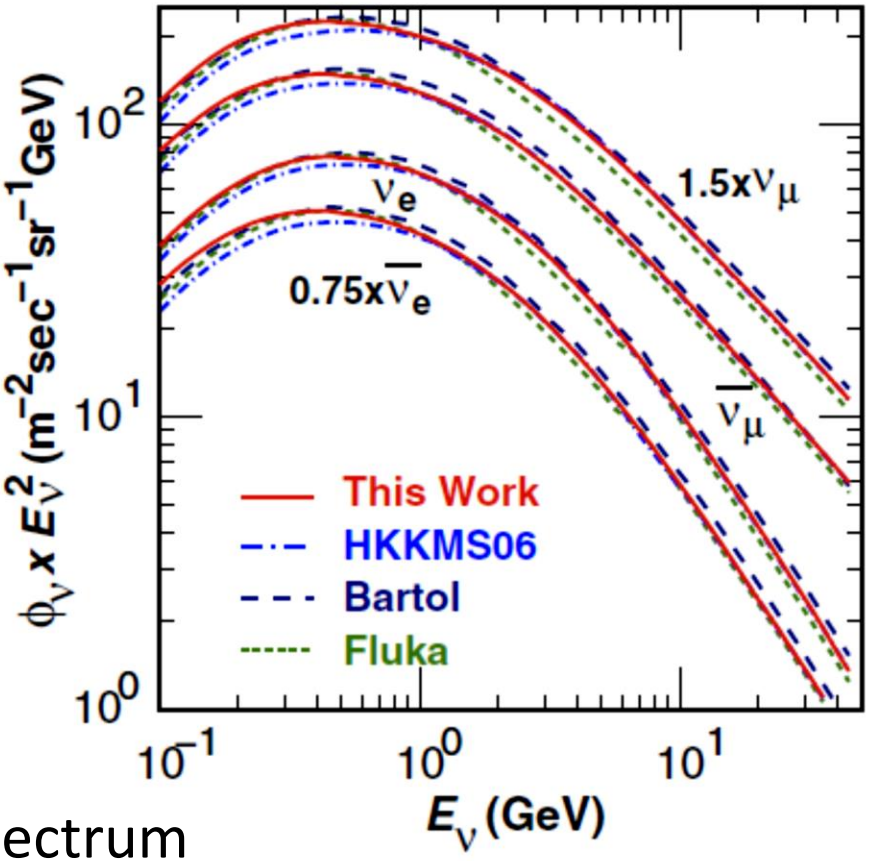


Atmospheric neutrino measurements in SK

Characteristics of atmospheric neutrino



Atmospheric ν energy spectrum



- Atmospheric neutrino energy spectrum

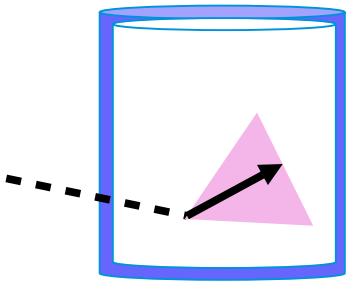
  Peaked at ~ several hundreds of MeV, Extended > TeV

- Zenith angle corresponds to travel length of neutrinos

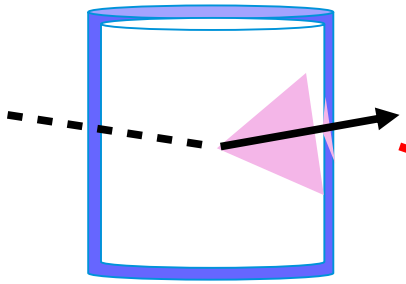
  Neutrino travel length from ~ 10 km to 13,000 km

Atmospheric neutrino ~ event topology in SK

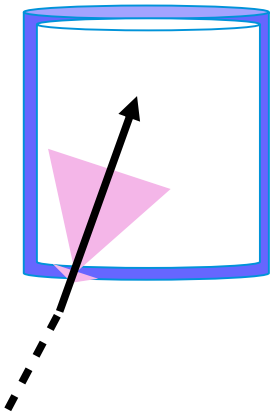
Fully Contained (FC)



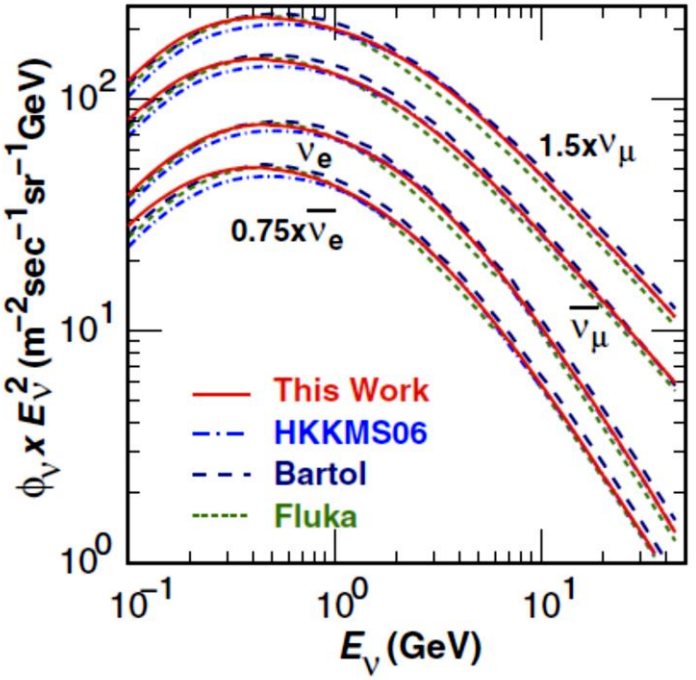
Partially Contained (PC)

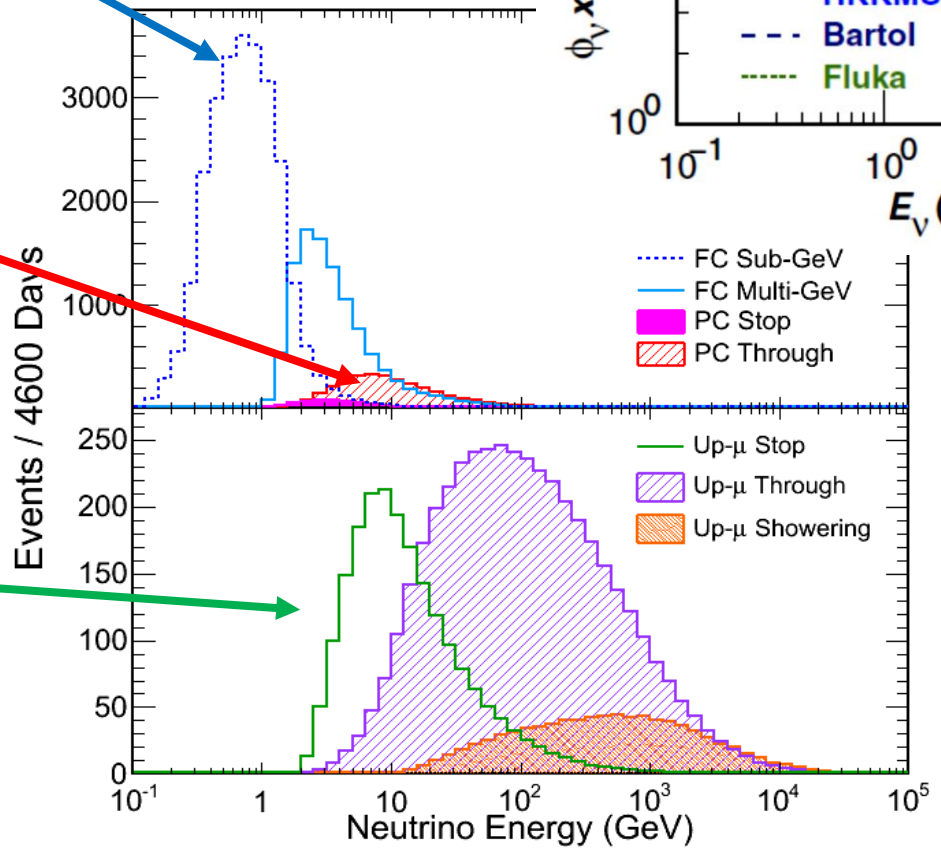


Upward-going Muons (Up-μ)



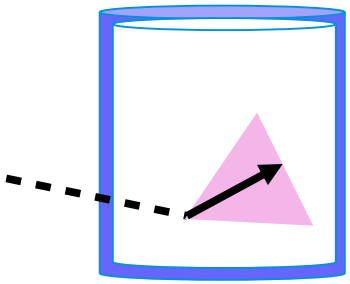
- Average energies
  - FC: ~ 1 GeV
  - PC: ~ 10 GeV
  - UpMu: ~ 100 GeV



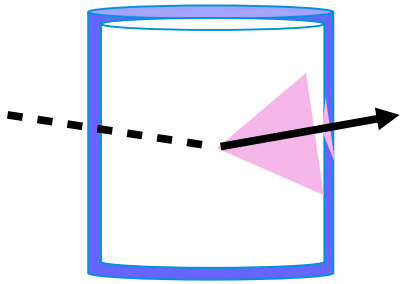


Atmospheric neutrino ~ Analysis samples in SK

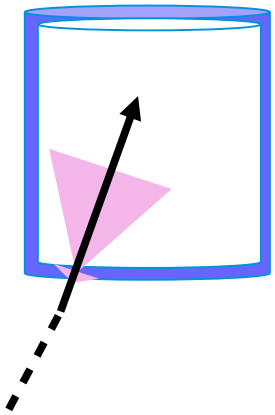
Fully Contained (FC)



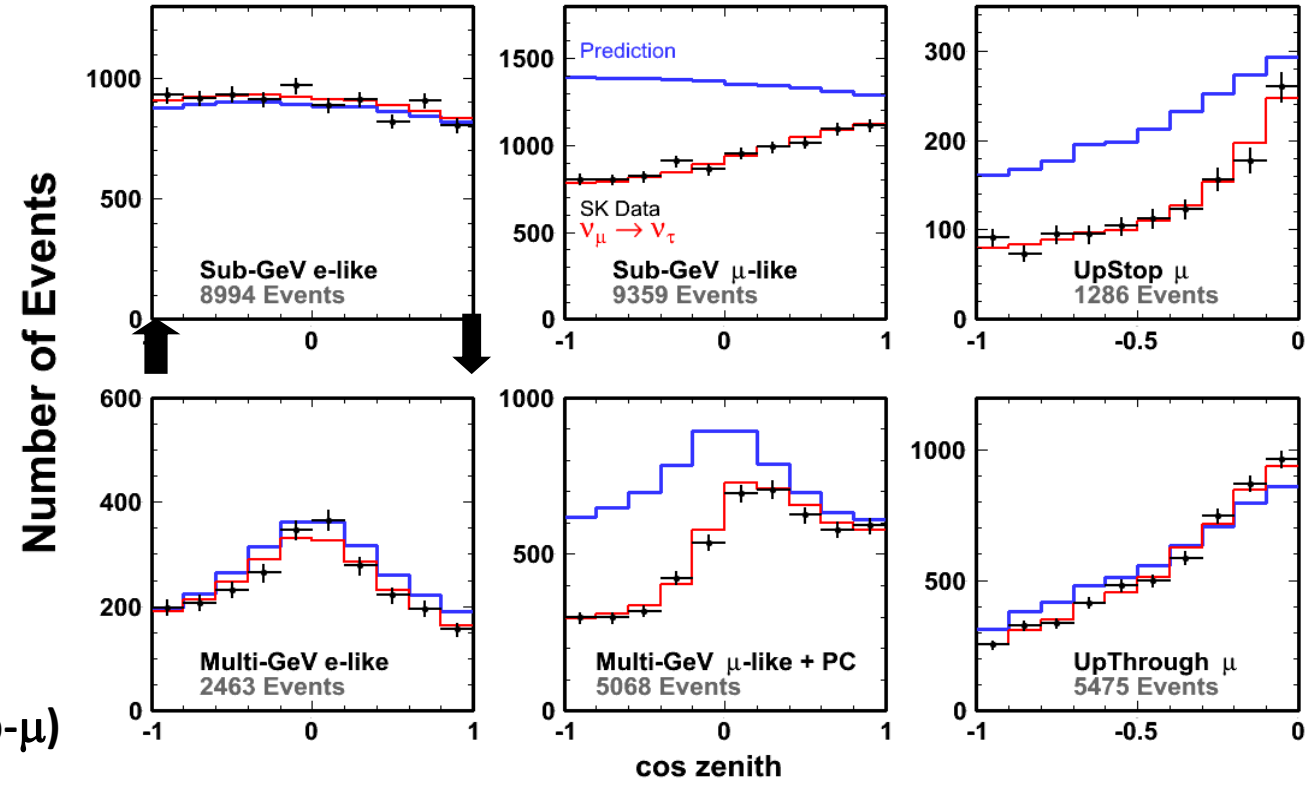
Partially Contained (PC)



Upward-going Muons (Up-μ)



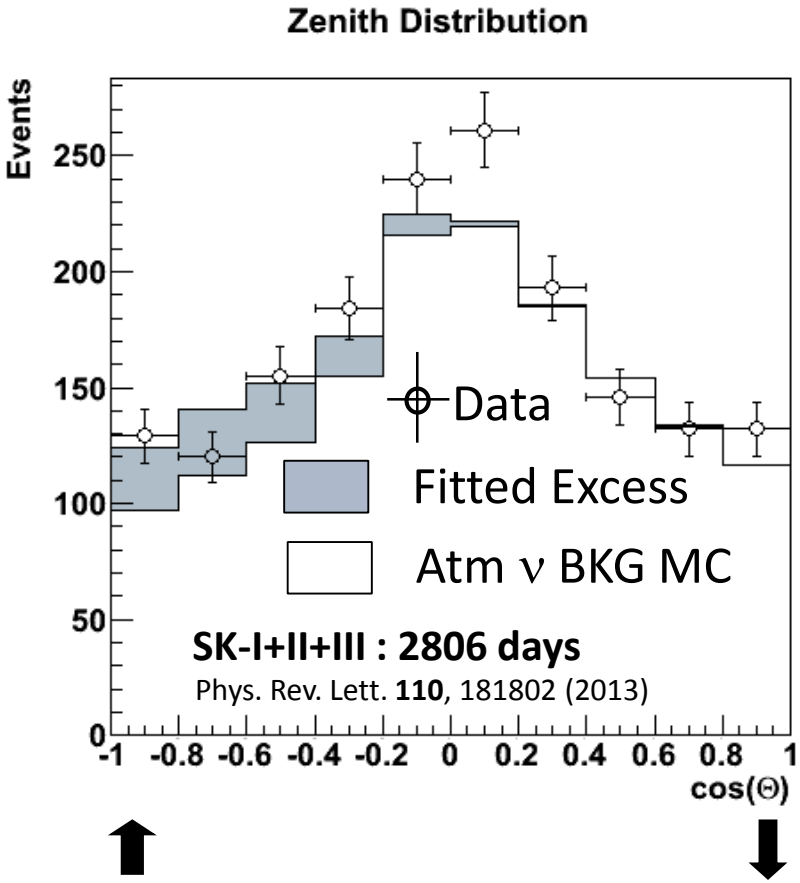
Zenith angle distribution of each sample



- In total 19 analysis samples
  (classified by ν flavors, event topologies, energies, …)
- *Fit to the data in bins of* ***$\cos\theta_{zenith}$ and momentum***
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in sub-dominant contributions
  Three-flavor effects, Sterile Neutrinos, LIV, …

Atmospheric neutrino oscillation analysis

~ Evidence for ν_τ Appearance at Super-K ~



Search for events ~ hadronic decay of τ lepton

Multi-ring e-like events

~ mostly DIS interactions

Actual event selection

performed by neural network

Total efficiency ~ 60%

Negligible primary ν_τ flux

~ ν_τ must be oscillation-induced

Expected only in upward-going

$\beta = 0$: no ν_τ

$$Data = \alpha(\gamma) \times bkg + \beta(\gamma) \times signal$$

Result	Background	DIS (γ)	Signal
SK-I+II+III	0.94 ± 0.02	1.10 ± 0.05	**1.42 ± 0.35**

180.1 $\pm$44.3 (stat) +17.8-15.2 (sys) events

~ **3.8 σ** excess (Expected 2.7 σ significance)

Neutrino oscillation studies using atmospheric ν

High statistics atmospheric neutrino data

~ Possibility in observing small distortion in ν_e

- Matter effect ~ from mass hierarchy

  Possible ν_e enhancement in several GeV passed through the earth core

- Solar term ~ from θ_{23} octant degeneracy

  Possible ν_e enhancement in sub-GeV

- Interference

  CP phase could be studied.

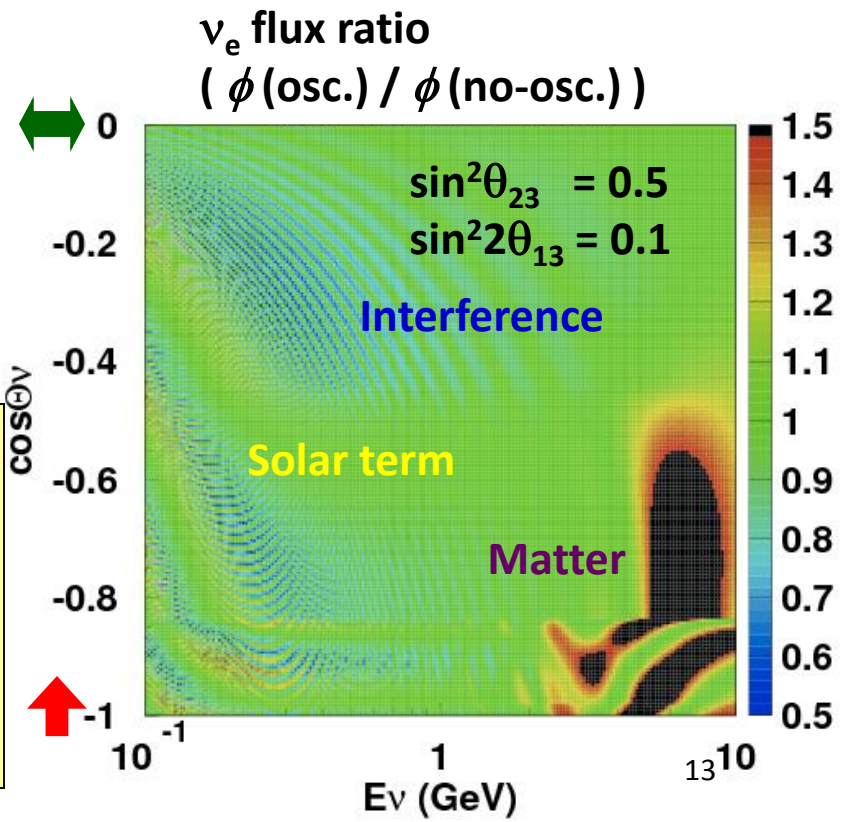
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m^2_{12}) + \Delta_3(\theta_{13}, \Delta m^2_{12}, \delta)$$

⬅ Matter effect

⬅ Solar term

⬅ Interference



Neutrino oscillation studies using atmospheric ν

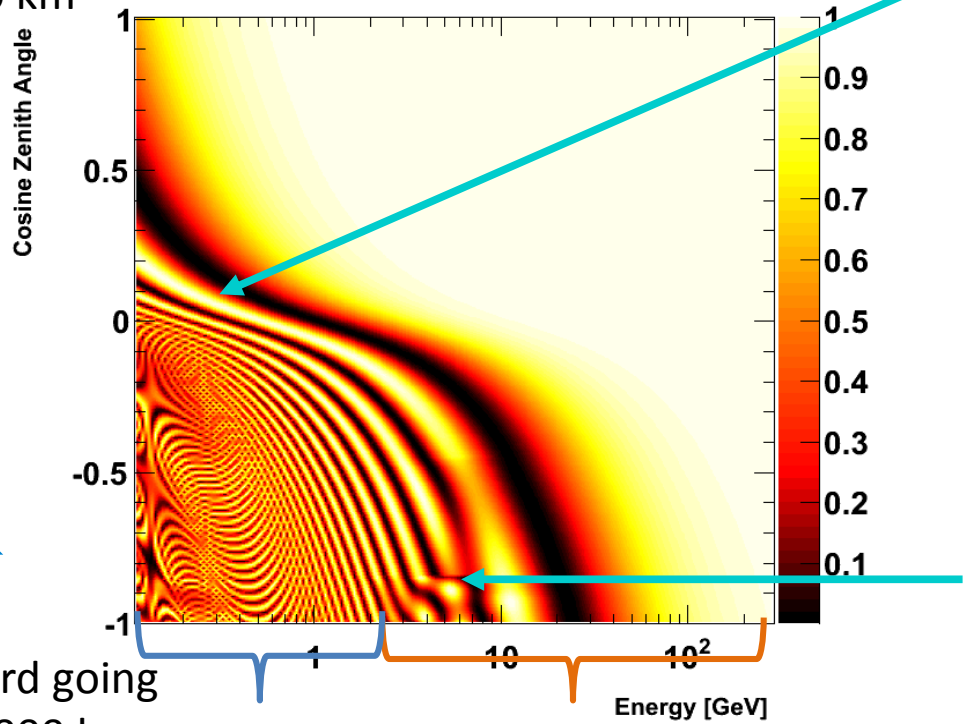
Oscillation Effects on Analysis Subsamples

θ_{23} is really 45° or < 45° or >45° ?

Ratio to two-flavor oscillation assumption

$\sim P(\nu_\mu \rightarrow \nu_\mu) \sim$

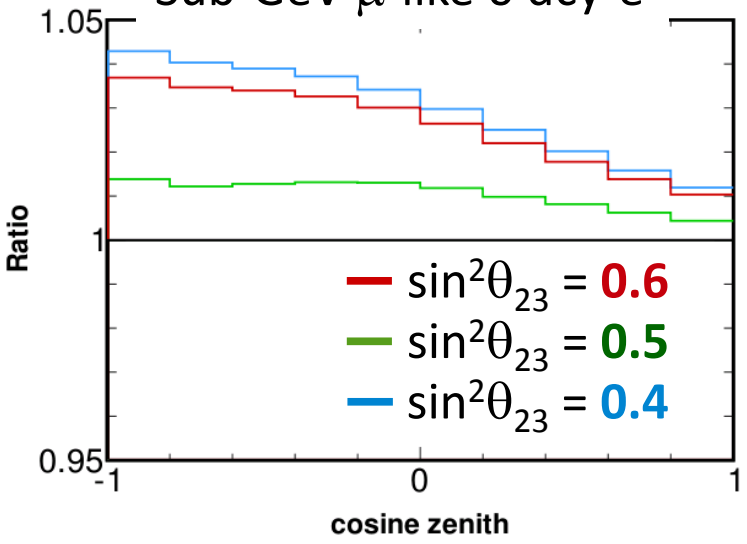
Downward going
L~100 km



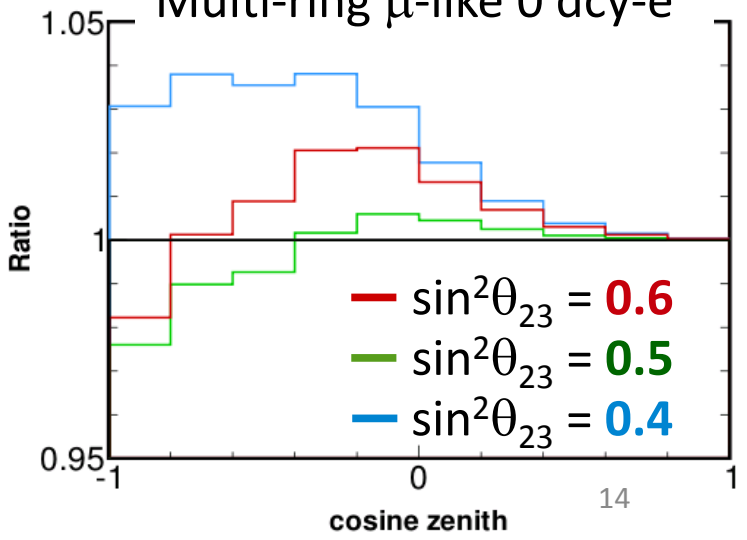
Upward going
L~10,000 km

"Sub-GeV" "Multi-GeV"

Sub-GeV μ-like 0 dcy-e



Multi-ring μ-like 0 dcy-e



Neutrino oscillation studies using atmospheric ν

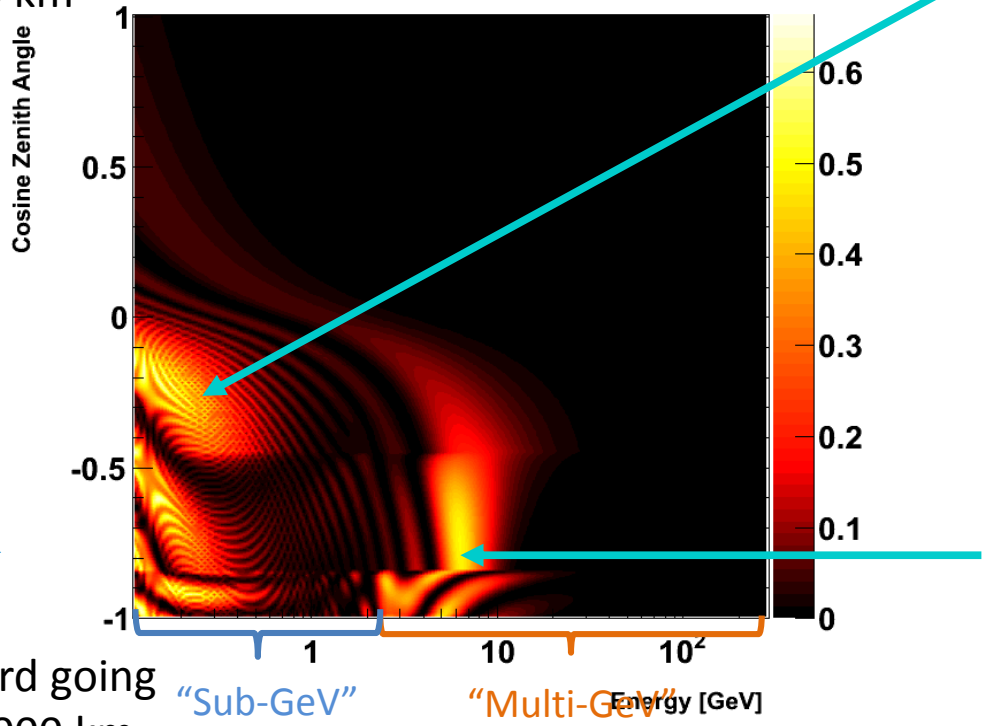
Oscillation Effects on Analysis Subsamples

Is CP in lepton sector violated?

Ratio to two-flavor oscillation assumption

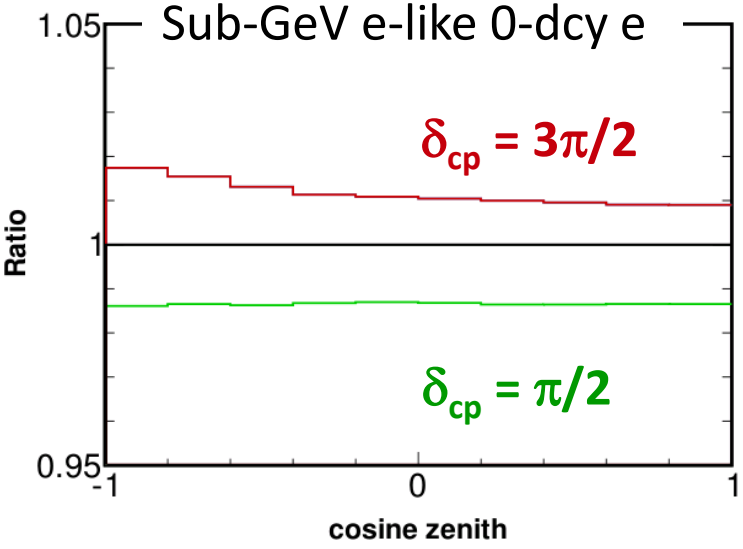
$\sim P(\nu_\mu \rightarrow \nu_e) \sim$

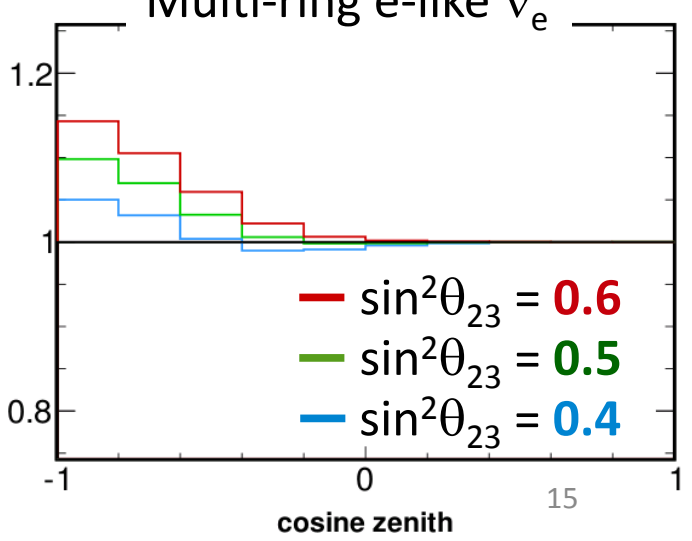
Downward going
L~100 km



Upward going
L~10,000 km

note : Appearance effects are roughly halved for the inverted hierarchy.



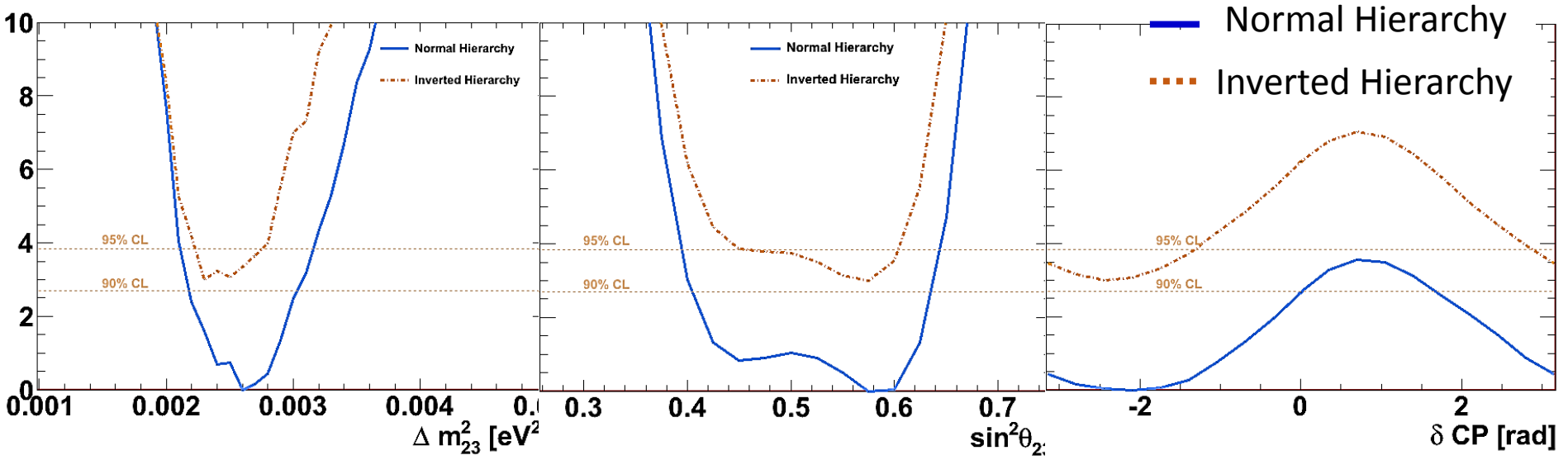


Neutrino oscillation studies using atmospheric ν

θ_{13} **Fixed** Analysis (NH+IH) SK Only

θ_{13} fixed to PDG2014 value ($\sin^2 2\theta_{13}$ =0.093 ±0.08)
uncertainty is included as a systematic error

Preliminary



Fit (517 dof)	χ2	δ_{cp} (rad)	$\sin^2\theta_{23}$	Δm^2_{23} (x10^{-3}eV^2)
SK (NH)	**582.4**	-2.09 (-0.67π)	0.575	2.6
SK (IH)	**585.4**	-2.44 (-0.78π)	0.575	2.3

Offsets in these curves show the absolute χ^2 diff. in the hierarchies.

Normal hierarchy is favored at $\chi^2_{NH} - \chi^2_{IH}$ = -3.0 (not significant still.)

Neutrino oscillation studies using atmospheric ν

θ_{13} **Fixed** Analysis (NH+IH) SK Only

Normal hierarchy favored

but $\chi^2_{IH} - \chi^2_{NH} =$ **- 3.0**

Not a significant preference

Driven by excess of upward-going e-like

consistent with the effects of θ_{13}

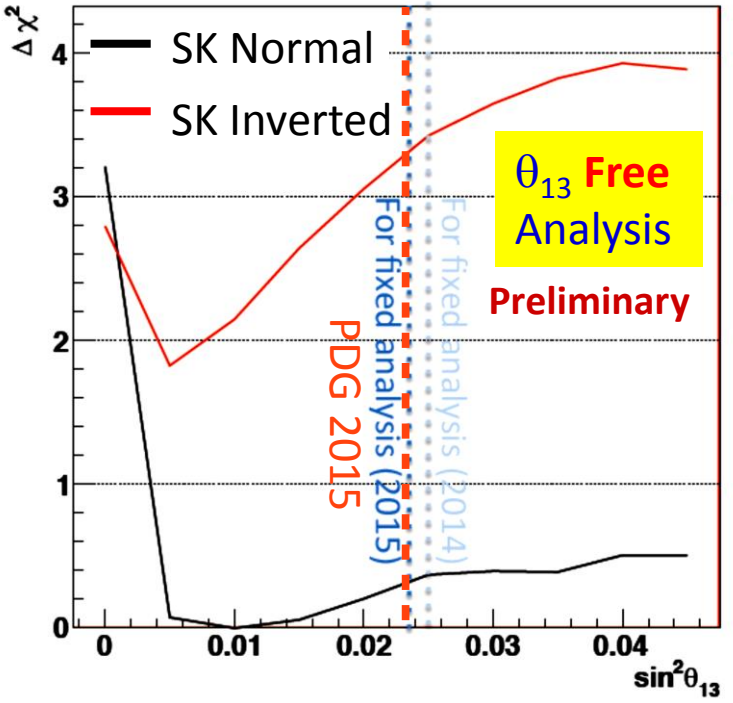
Primarily in SK-IV data

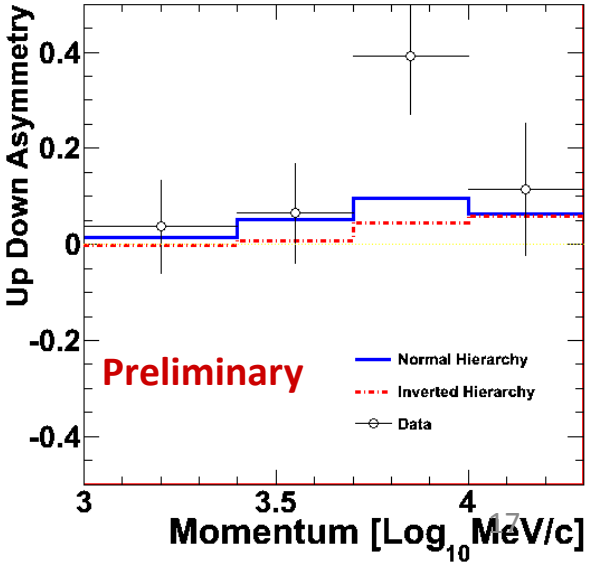
New multi-ring e-like sample also pulls the fit towards the NH

Fit for θ_{13} now weakly favors $\theta_{13} > 0$

Rejection around $\delta_{cp} \sim 0.2\pi$ was driven by excess in Sub-GeV electron events

Constraint is consistent with sensitivity





T2K experiment

Tokai to Kamioka long baseline neutrino oscillation experiment (T2K)

Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

- *Search for the ν_e appearance*
  → measure θ_{13}
- *Precision measurements of oscillation parameters with ν_μ disappearance*
  → $\delta(\Delta m^2_{23}) \sim 1\times10^{-4}$ eV^2 , $\delta(\sin^2 2\theta_{23}) \sim 0.01$
- *Study CP violation in the lepton sector (& mass hierarchy)*

T2K neutrino beam ~ Off axis beam ~

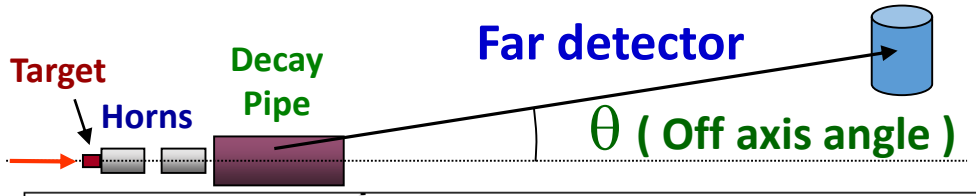
Maximize sensitivity in oscillation studies

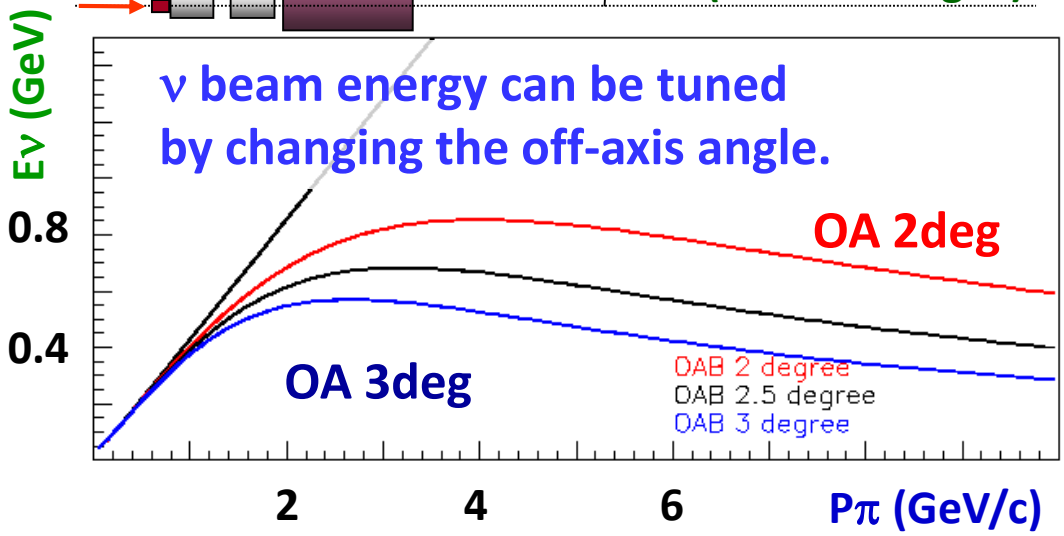
→ Use narrow band beam with peak energy at the oscillation maximum

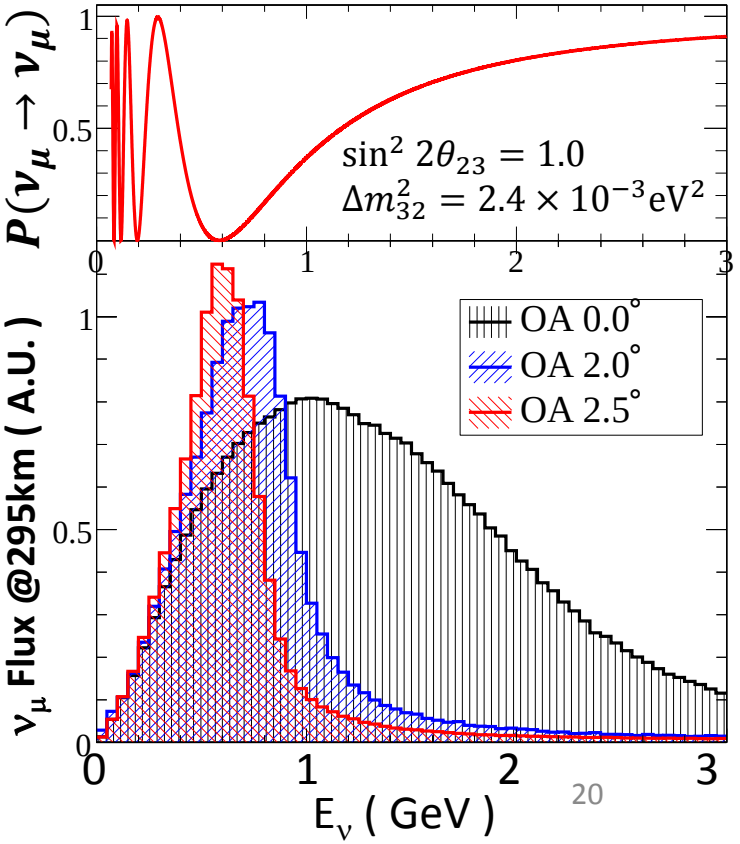
→ ***Off axis beam*** (ref.: BNL-E889 Proposal)

- Quasi-monochromatic beam ~ suppressed high energy ν
- Energy is adjustable (Change off axis angle)

Important to monitor beam direction!
(1mrad ~ peak E_ν shifts by ~16 MeV)







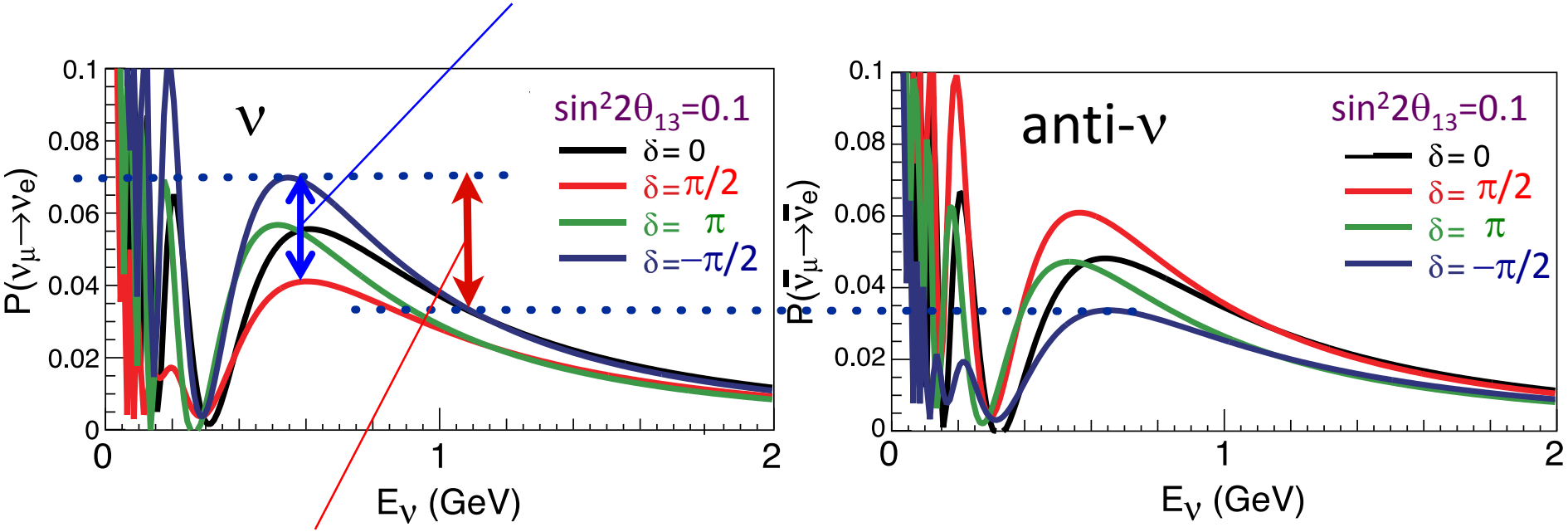
Neutrino mixing parameter measurements in T2K

ν_e appearance channel

~ Study of CP violation in lepton sector

Two methods

Use θ_{13} constraints from reactor $\bar{\nu}_e$ disappearance

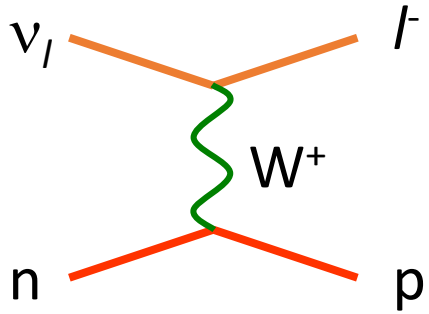


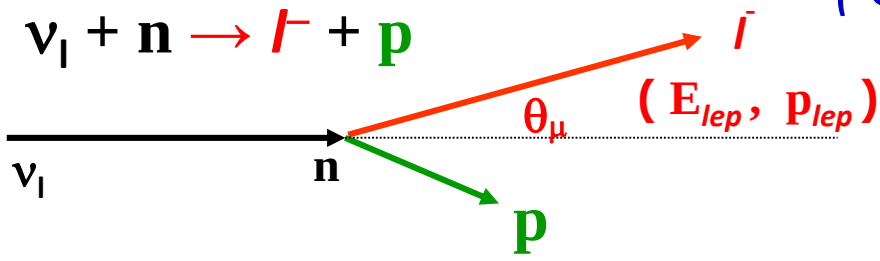
Compare difference between ν and $\bar{\nu}$ oscillations

Recently, T2K is running with anti-neutrino configuration!

Neutrino mixing parameter measurements in T2K

Use charged lepton from charged current quasi-elastic scattering (CCQE)



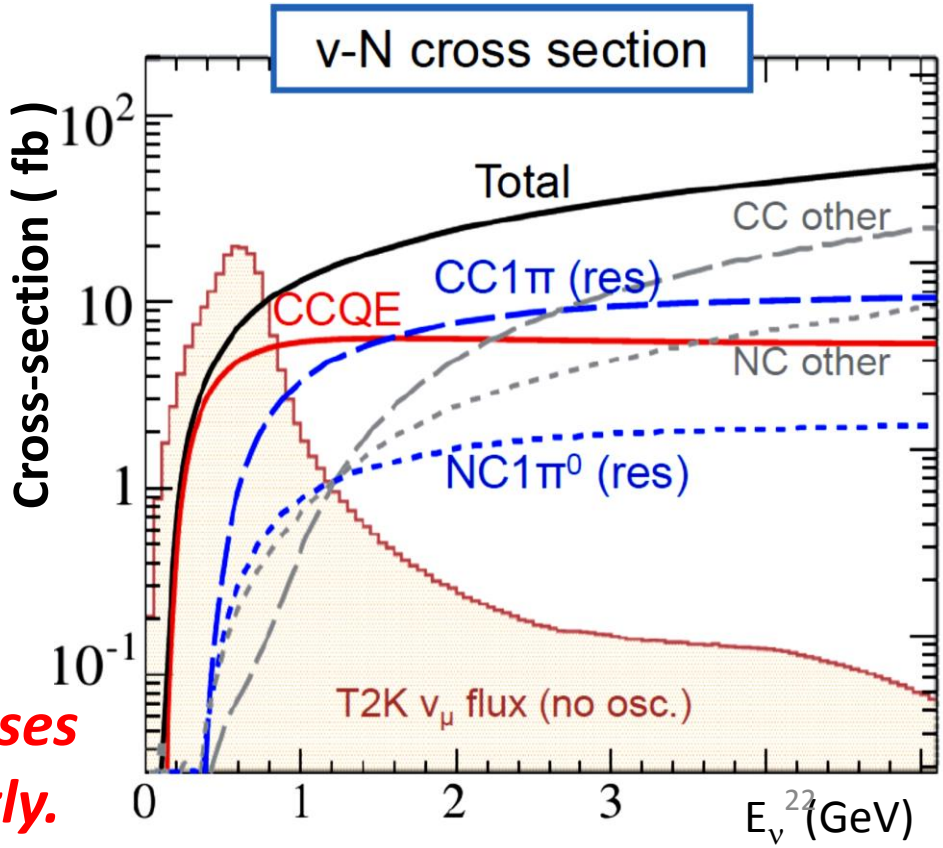


CCQE is the dominant interaction around the oscillation peak ~ flux peak.

E_ν can be reconstructed from measured E_{lep} & θ_{lep}

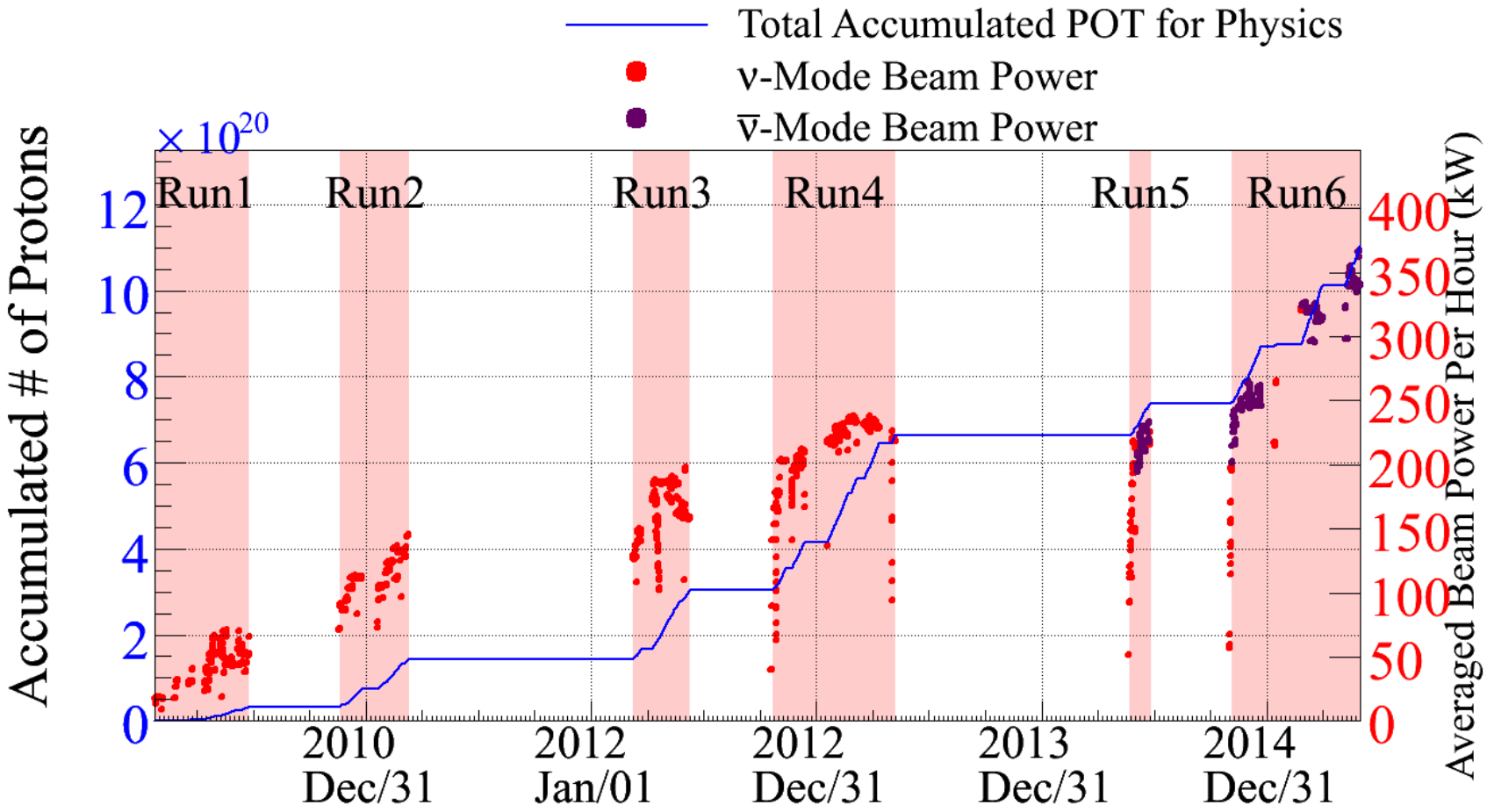
$$E_{\mathrm{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

(E_b : Binding energy)



Some of the T2K oscillation analyses use p_μ and θ_μ distribution directly.

T2K status ~ accumulated number of protons on target



By June 2015, accumulated POT is ***11 x 10²⁰*** POT

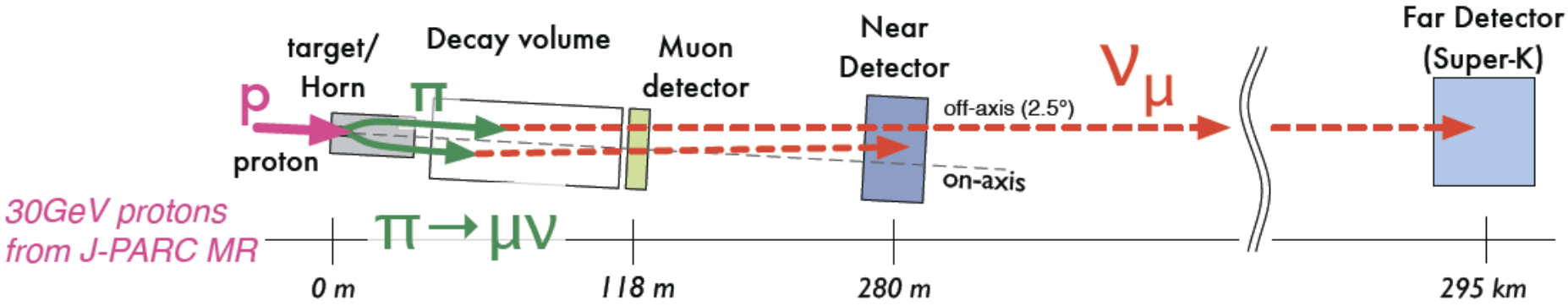
(~14 % of projected # of POT)

Neutrino mode running 7.0x10²⁰ POT

Anti neutrino mode running 4.0x10²⁰ POT

Beam power achieved at ***370kW*** in June 2015.

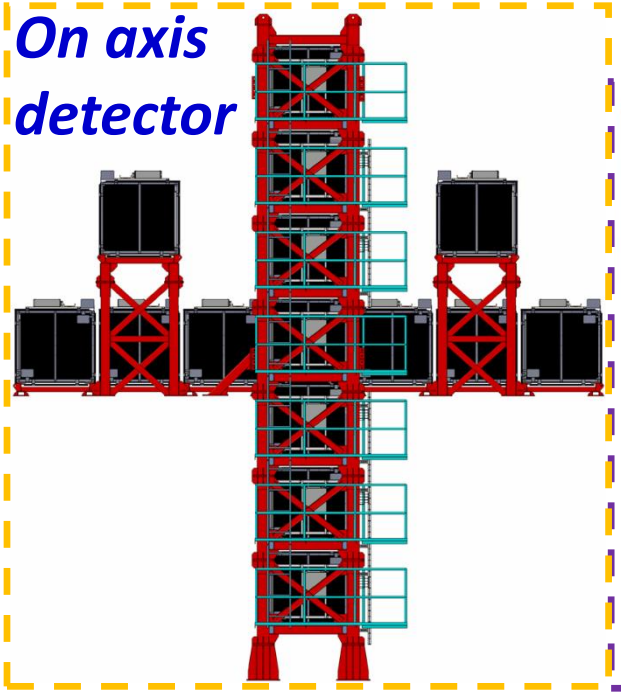
T2K ~ Schematic diagram of the experiment



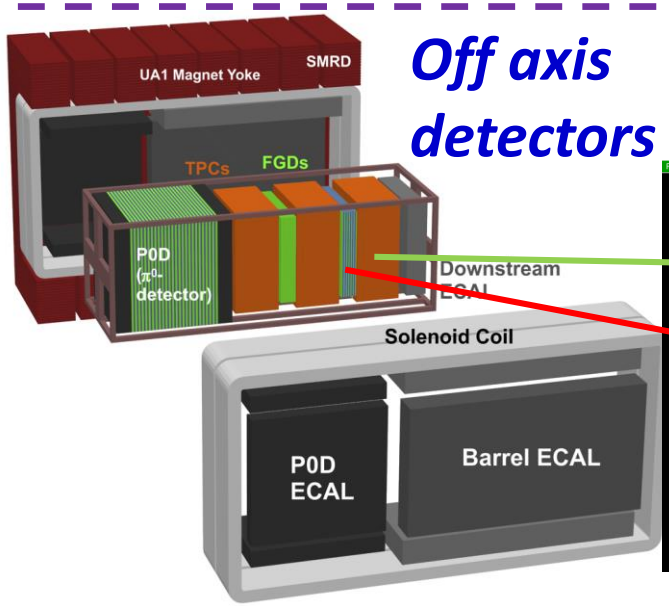
- On axis near ν detector ***INGRID***
  - ν interaction rate
  - ν beam direction monitor
- Off axis detectors
  - neutrino flux measurements
  - neutrino interaction studies

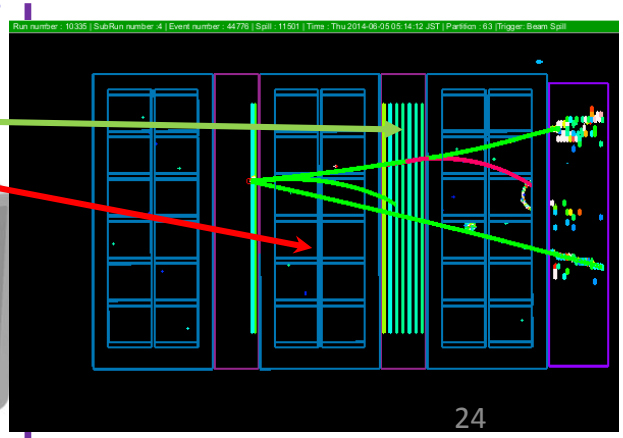
In the UA1 magnet (0.2 T)

On axis detector



Off axis detectors





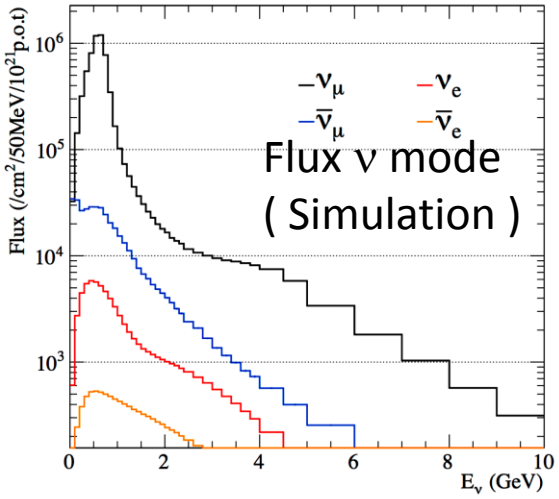
T2K experiment ~ Analysis strategy

Extracting the “oscillation parameters” from observables

~ ***compare the data and the prediction with oscillations***.

Prediction

Based on Monte-Carlo simulation with various constraints from the measurements



ν flux

ν cross sections

Beam simulation program
(FLUKA + GEANT3 w/ GCALOR)
+ π, K production data (NA61 etc.)

ν interaction simulation program
(NEUT)
+ External constraints (data)

Near detector measurements
to constrain uncertainties
of neutrino flux and
neutrino interaction models

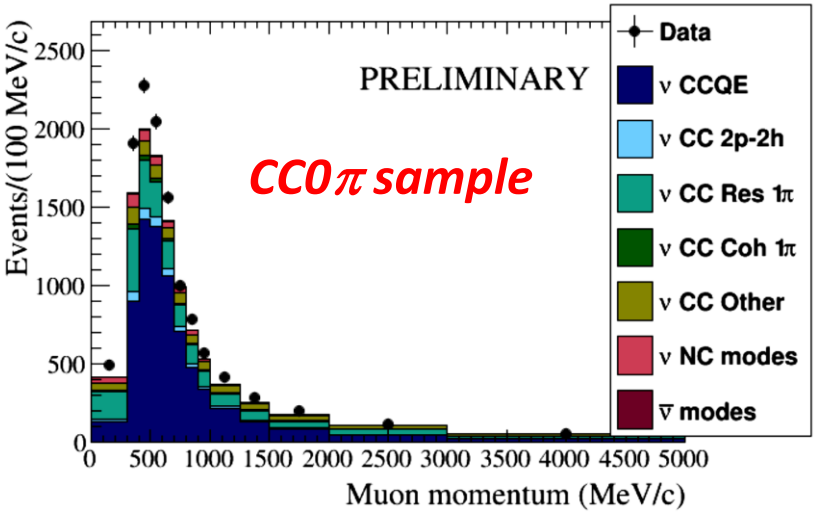
prediction in SK

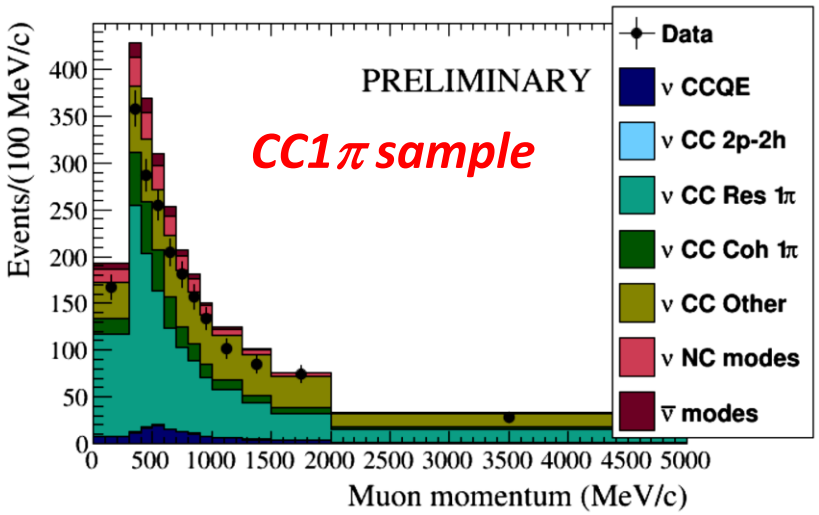
T2K Near detector measurements

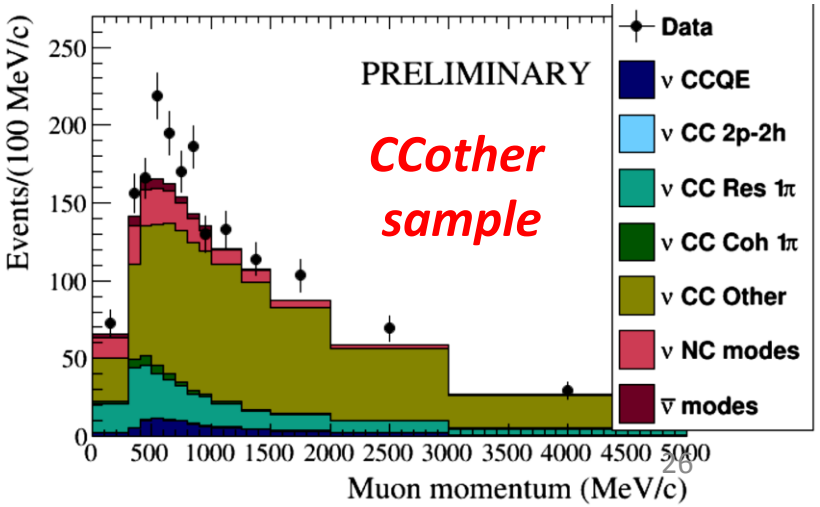
For the oscillation analyses, we performed the fit with ND280 data to determine/ constrain the neutrino interaction parameters and neutrino flux simultaneously.

3 sub-samples from neutrino running

- Events with μ^- and no pion (CC0π)
  CCQE enriched
- Events with μ^- and 1 $\pi^\pm$ (CC1π)
  CC 1π enriched
- Other events with μ- (CC Other)
  CCDIS enriched







T2K Near detector measurements

For the oscillation analyses, we performed the fit with ND280 data to determine/ constrain the neutrino interaction parameters and neutrino flux simultaneously.

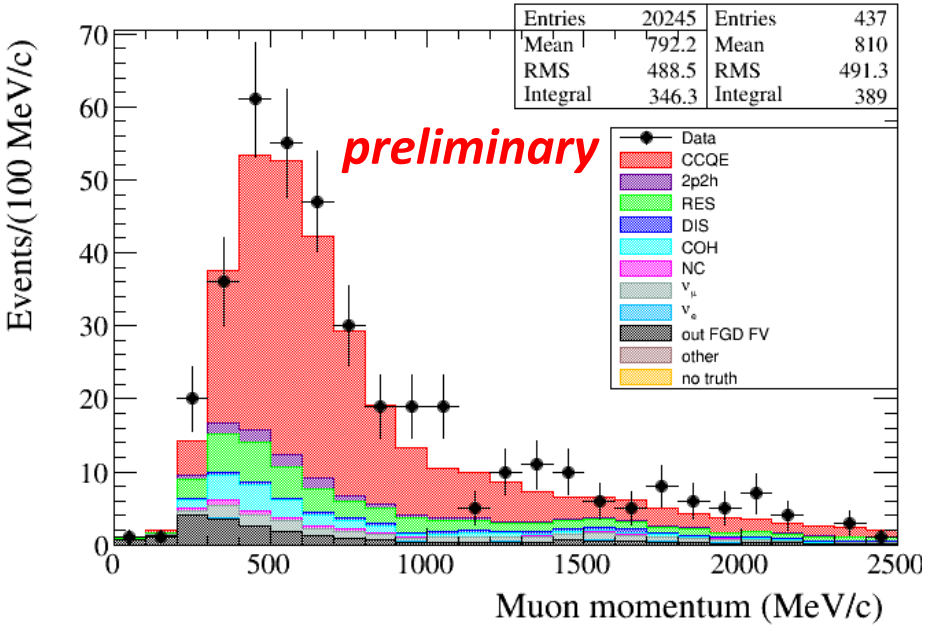
2 sub-samples of $\bar{\nu}$ in anti-neutrino running period.

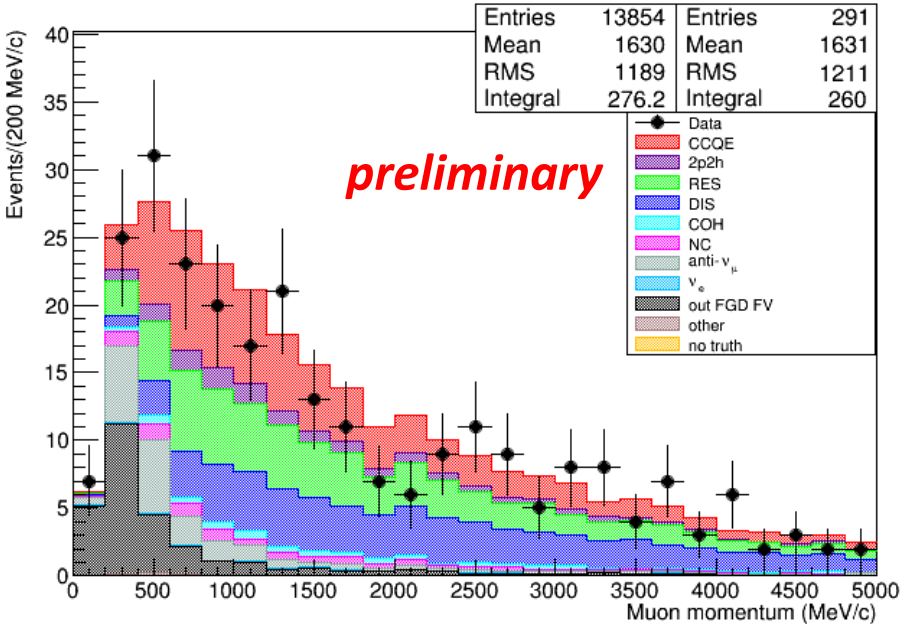
- Events with μ^+ and only 1 track reconstructed

  CCQE enriched

- Events with μ^+ and there are more than 1 track reconstructed

  Inclusive (less CCQE)





(ν candidaes in $\bar{\nu}$ running are also used)

T2K SK event selections

ν_μ / $\bar{\nu}_\mu$ disappearance

~ for θ_{23} measurement

Use ν_μ CCQE interaction

- Fully contained
- Vertex in the fiducial volume
- **One reconstructed μ-like ring**
- Rec. momentum of μ
  >200 MeV/c
- 0 or 1 decay electrons
  Reject events with invisible π

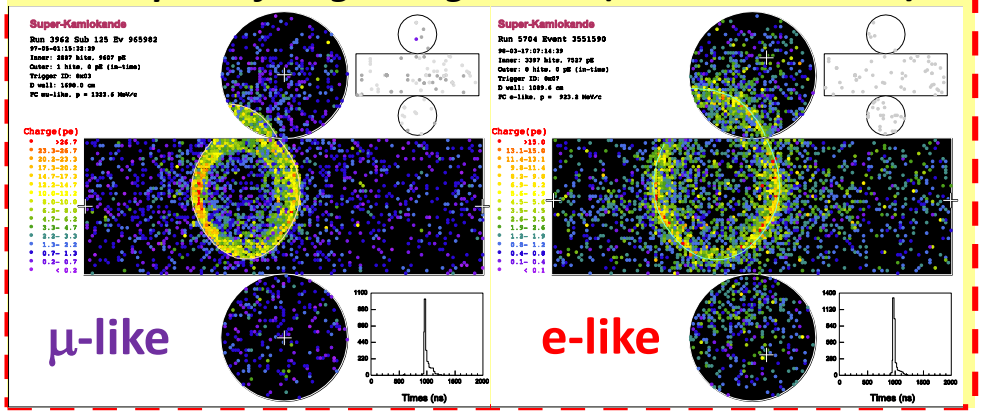
ν_e / $\bar{\nu}_e$ appearance

~ for θ_{13} measurement and δ_{CP}

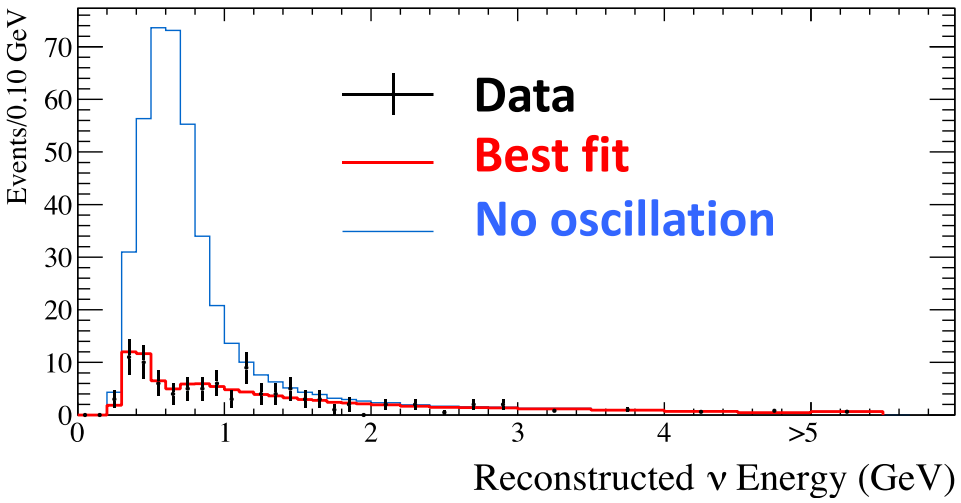
Use ν_e CCQE interaction

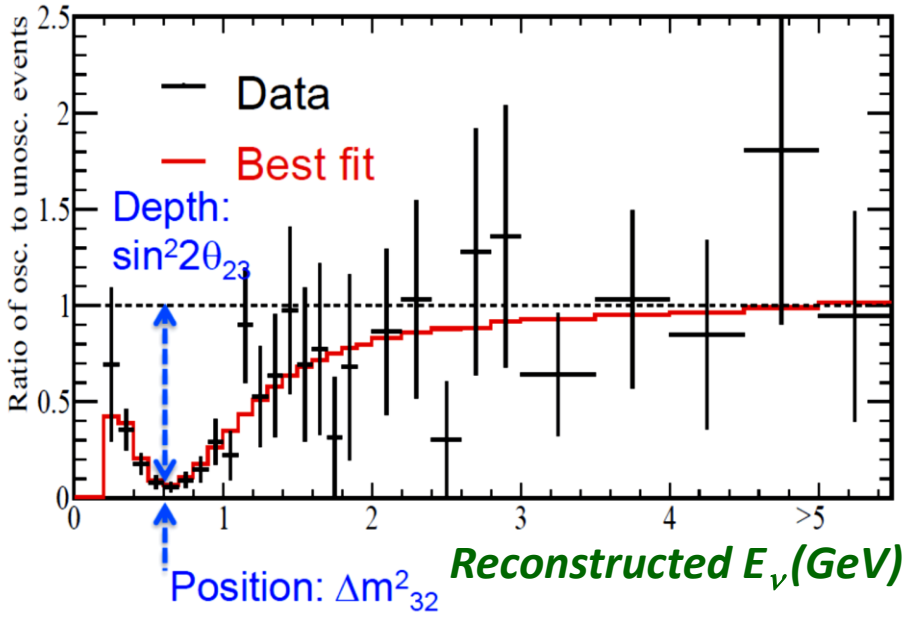
- Fully contained
- Vertex in the fiducial volume
- **One reconstructed electron-like ring**
- Visible energy >100MeV
  Reject low energy NC events and electron from "invisible" μ and π
- No decay-electron
  Reject events with invisible μ and π
- Reconstructed E_ν < 1.25GeV
- Not π^0 like

Examples of single-ring events (non-T2K events)



T2K neutrino oscillation analysis ν_μ disappearance





Extracting oscillation parameters

Maximum likelihood fit based on

# of observed events in SK (N_{SK}) and

reconstructed energy of neutrino (E_ν^{rec})

or kinematics of observed lepton (p_μ, θ_μ)

$$L = L_{norm.} \times L_{shape} \times L_{syst.} \times L_{osc.}$$

Constraints from the other exp's.

$\sin^2\theta_{12} = 0.312 \pm 0.016$

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV²/c⁴

$\sin^2\theta_{13} = 0.0251 \pm 0.0035$ (from PDG 2012), δ_{CP} is unconstrained.

T2K neutrino oscillation analysis

ν_μ disappearance

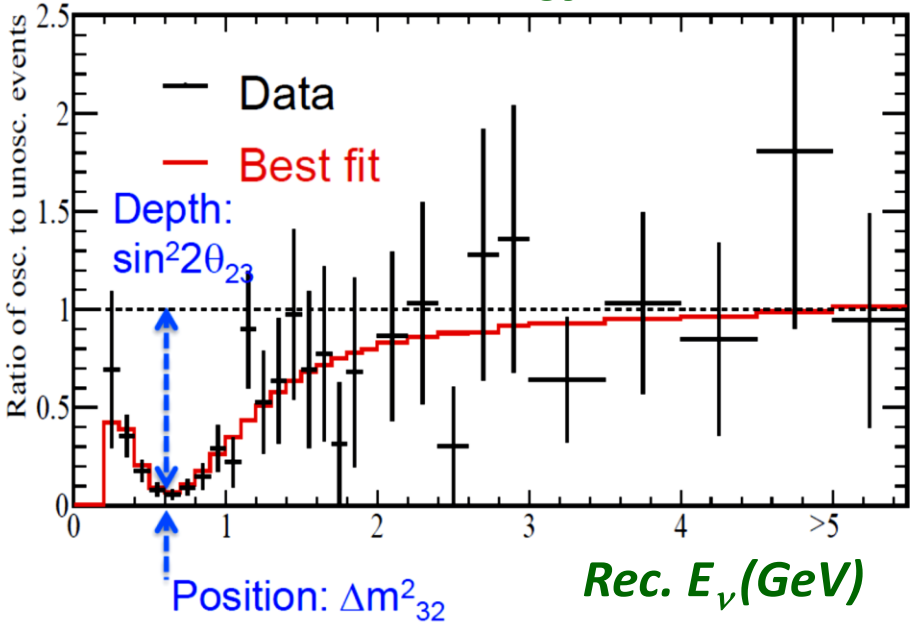
(Run 1 ~ 4 : 6.57 x 10^{20} P.O.T.)

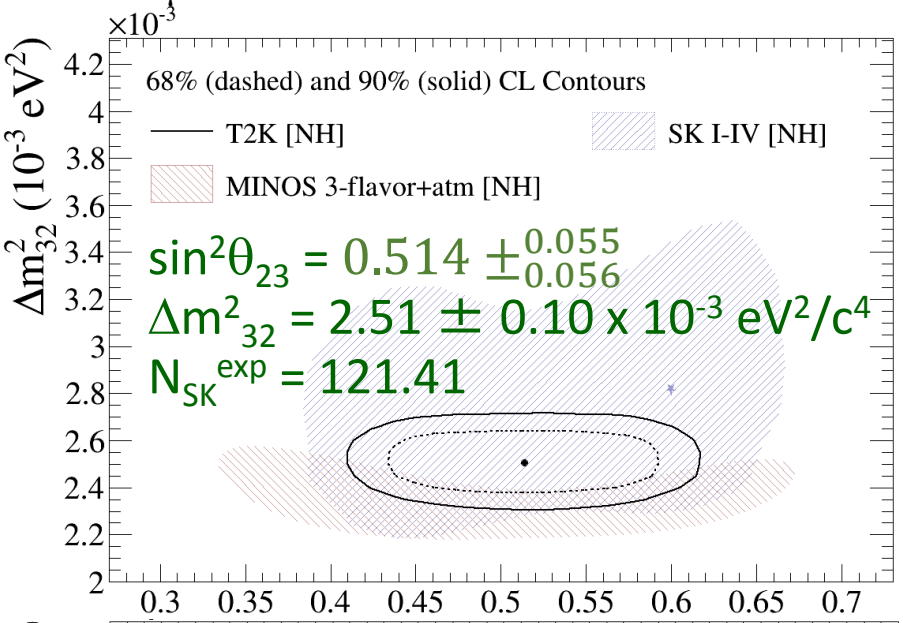
Expected # of events without oscillation

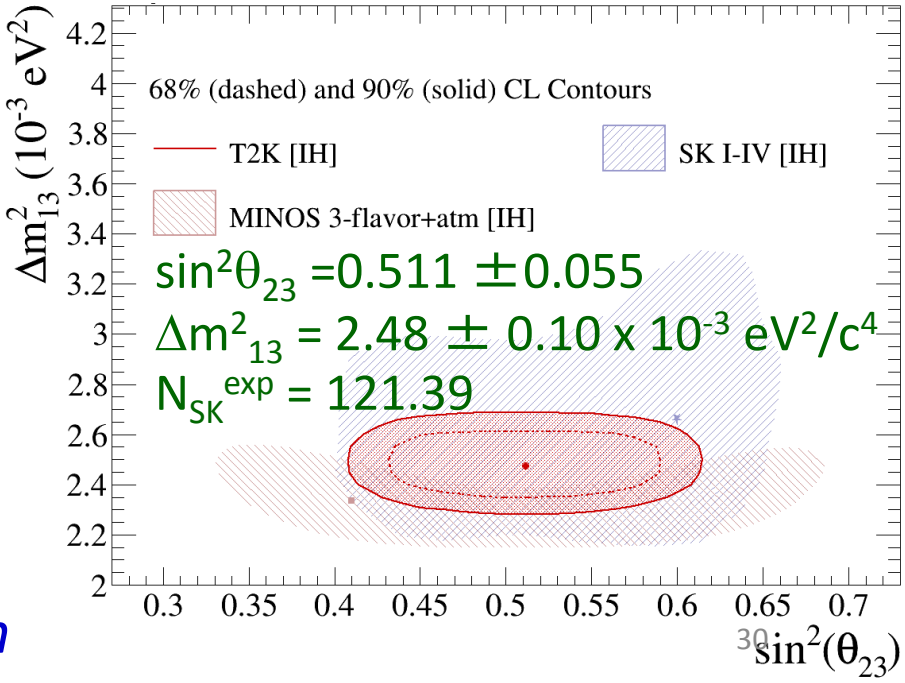
$= 446.0 \pm 22.5\ (syst.)$

Observed # of events ***= 120***

Reconstructed ν energy







Best sensitivity of θ_{23} measurements indicates maximum oscillation

T2K neutrino oscillation analysis

ν_e appearance

(Run 1 ~ 4 : 6.57 x 10^{20} P.O.T.)

Expected # of background events

$= 4.9 \pm 0.6\ (\ syst.\ )$

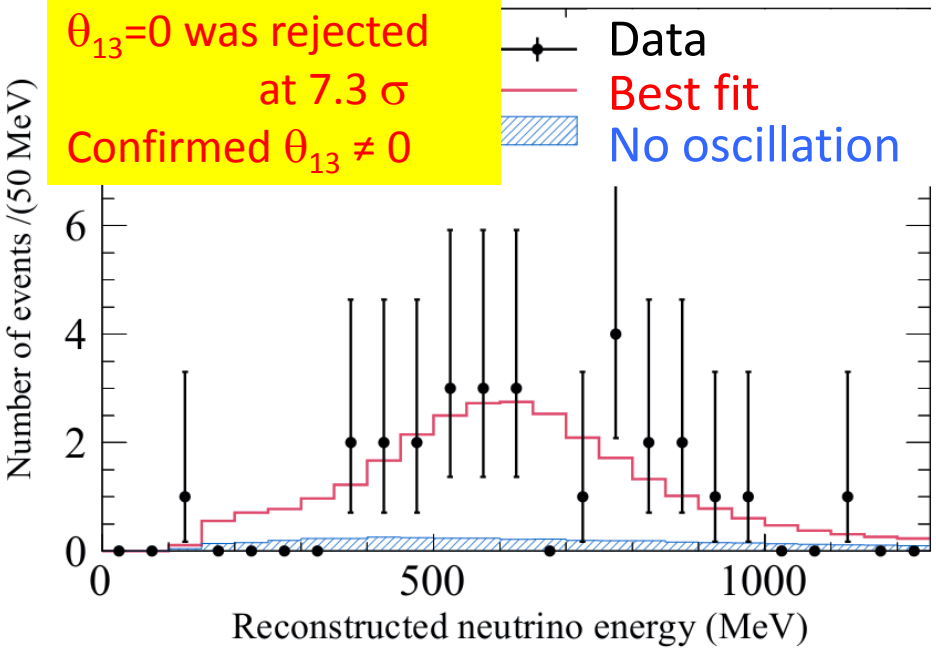
$\sin^2(2\theta_{13})=0$

Observed # of events ***= 28***

Reconstructed ν energy

θ_{13}=0 was rejected at 7.3 σ

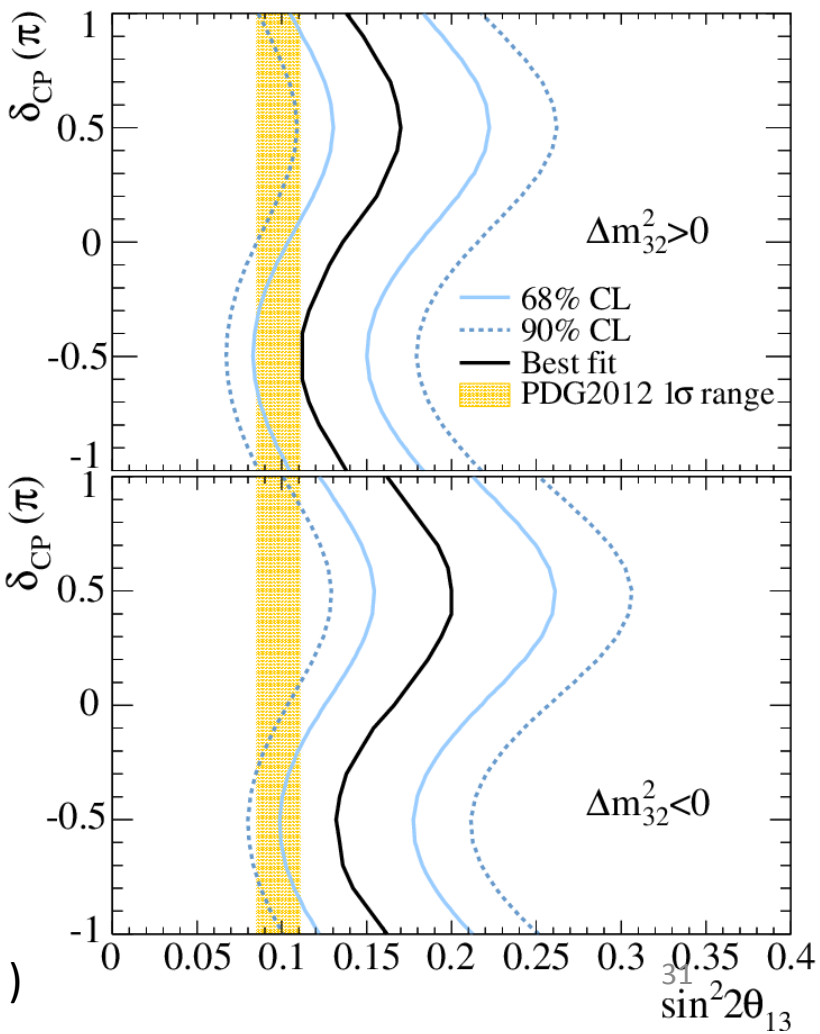
Confirmed $\theta_{13} \neq 0$



$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ (normal hierarchy)

$0.170^{+0.044}_{-0.037}$ (inverted hierarchy)

Allowed regions of $\sin^2 2\theta_{13}$ for δ_{CP}



T2K neutrino oscillation analysis

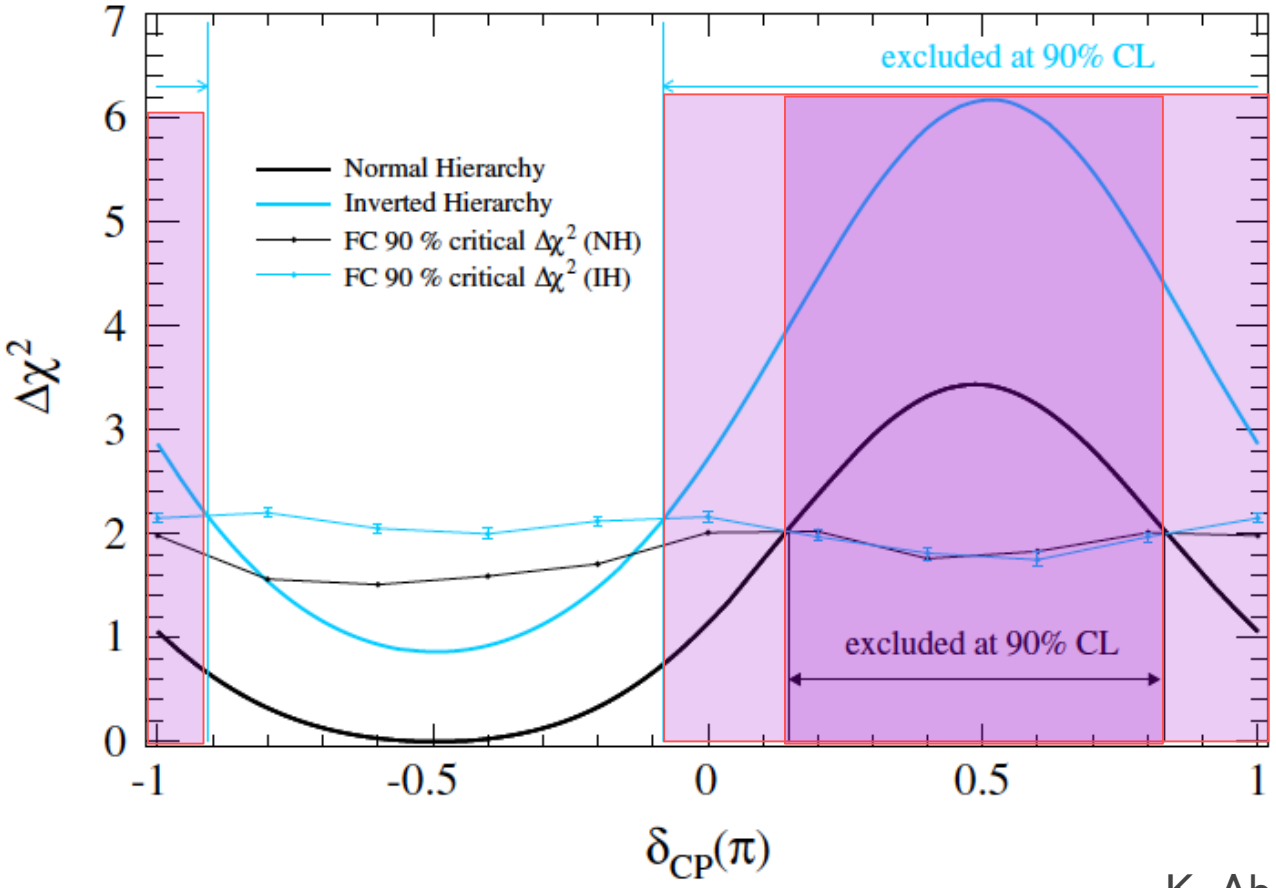
ν_μ disappearance + ν_e appearance

Use both ν_μ and ν_e events to constrain δ_{CP}

$\sin^2 2\theta_{13}$ from reactor experiment

(Run 1 ~ 4 : 6.57 x 10^{20} P.O.T.)

$$\sin^2 2\theta_{13} = 0.095 \pm 0.01$$



90% excluded regions

Normal hierarchy

$0.15\pi \sim 0.83\pi$

Inverted hierarchy

$-1.00\pi \sim -0.91\pi$

$-0.08\pi \sim 1.00\pi$

K. Abe *et al.* (T2K Collaboration)
Phys. Rev. D 91, 072010

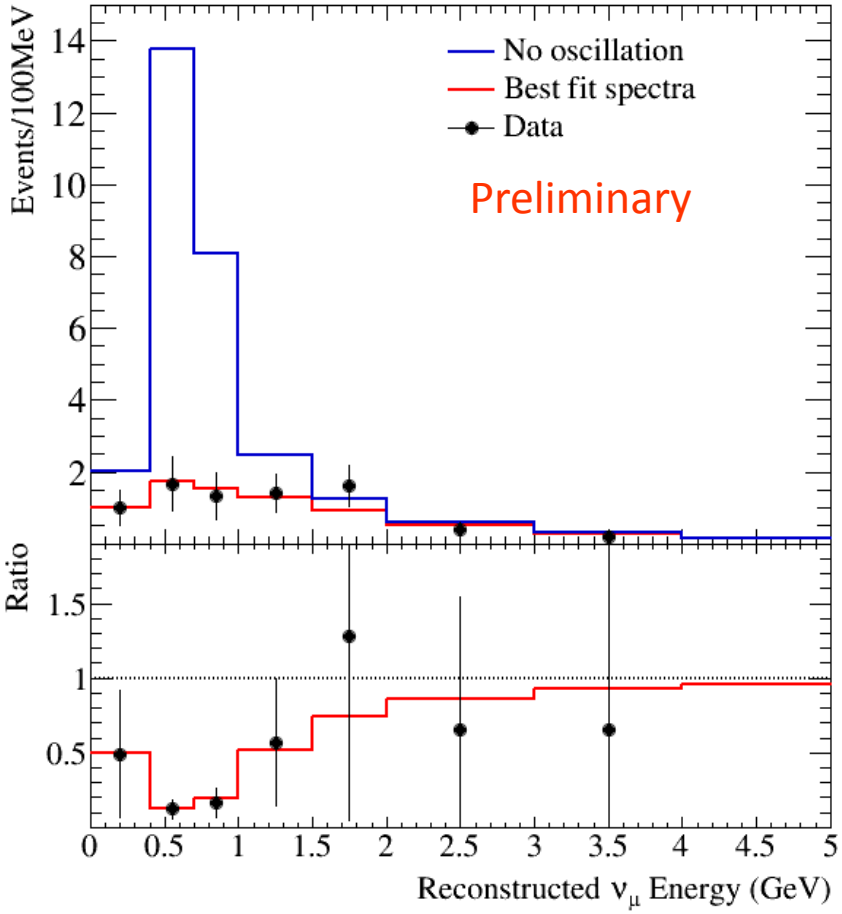
T2K neutrino oscillation analysis $\bar{\nu}_\mu$ disappearance

(Run 5 & 6 : 4.0x10^{20} POT)

Expected # of events without oscillation = 103.6 ± 12.0 (*syst.*)

Observed # of events ***= 34***

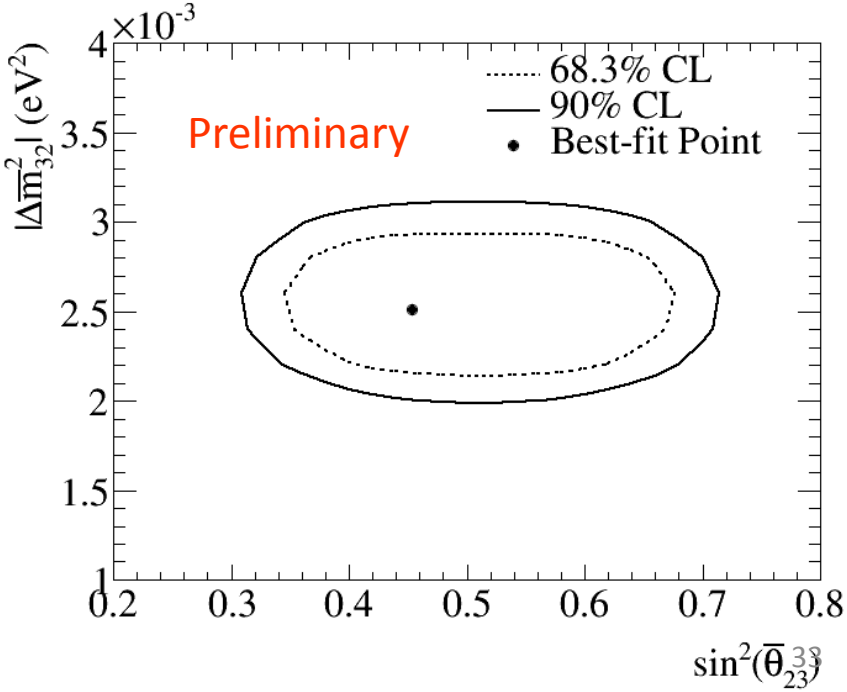
Reconstructed ν energy



Obtained neutrino oscillation parameters

$\sin^2\theta_{23} = 0.45 \pm^{0.24}_{0.11}$

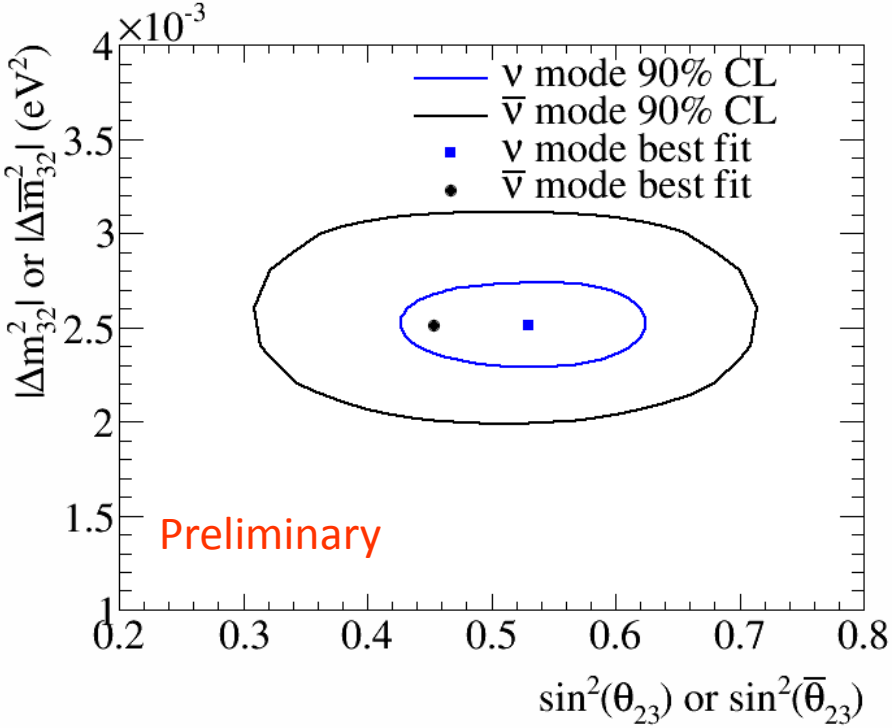
$\Delta m^2_{23(13)} = 2.51 \pm 0.28 \times 10^{-3}$ eV^2



T2K neutrino oscillation analysis

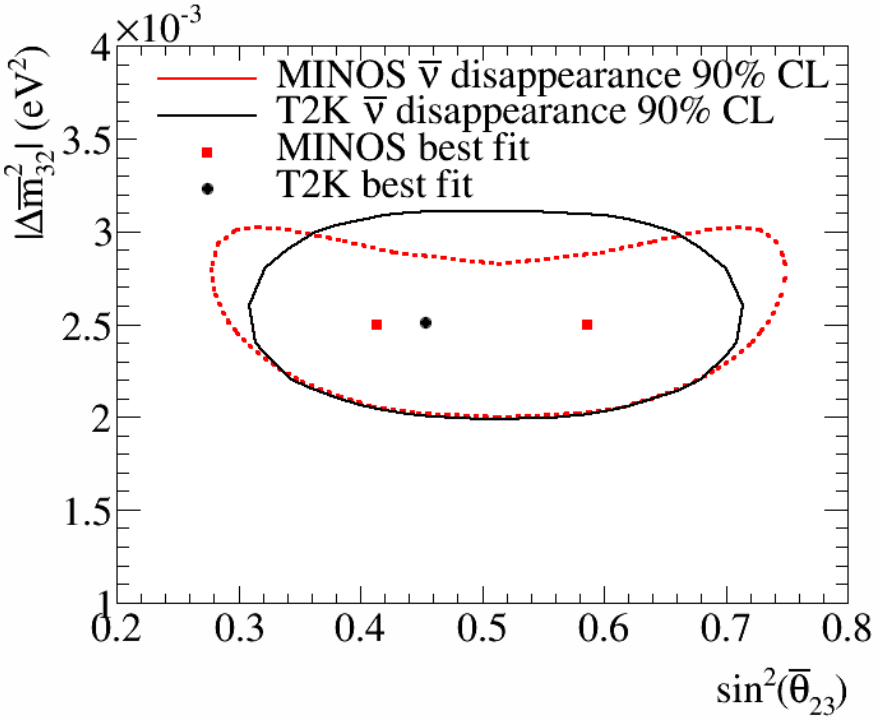
ν_μ and $\bar{\nu}_\mu$ disappearance

Comparisons between $\bar{\nu}_\mu$ and ν_μ disappearances



Results are consistent between neutrino and anti-neutrino.

Comparison with MINOS ($\bar{\nu}_\mu$ disappearance)



Tighter constraints on θ_{23} than MINOS experiments

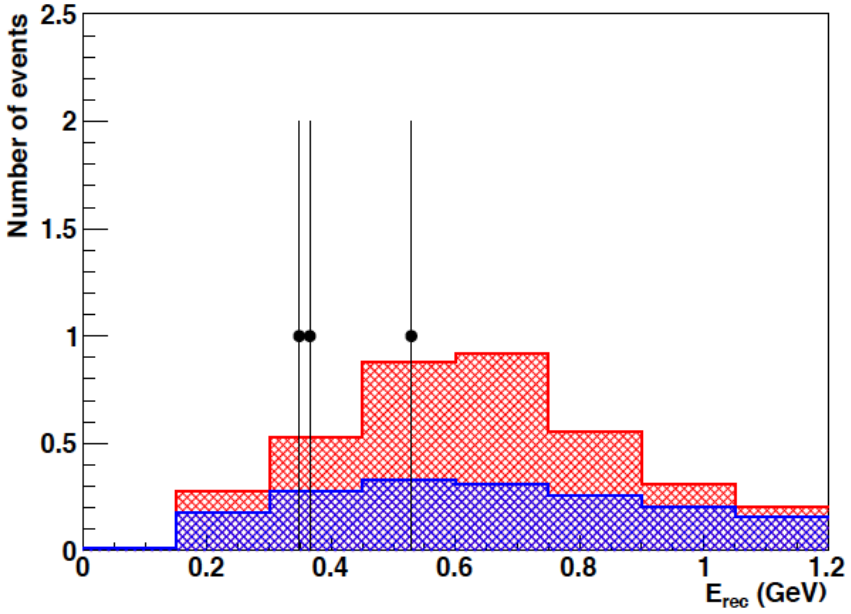
MINOS	3.3×10^{20}POT
T2K	4.0×10^{20}POT

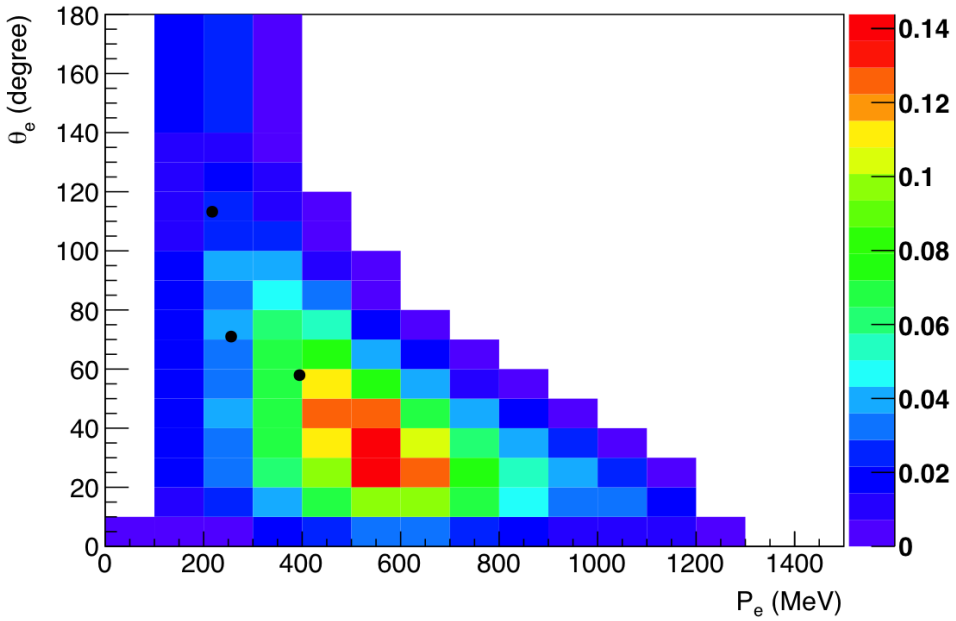
T2K neutrino oscillation analysis $\bar{\nu}_e$ appearance

(Run 5 & 6 : 4.0×10^{20} POT)

Observed # of events = 3

Expected # of background events = 1.77 (NH) or 1.70 (IH)





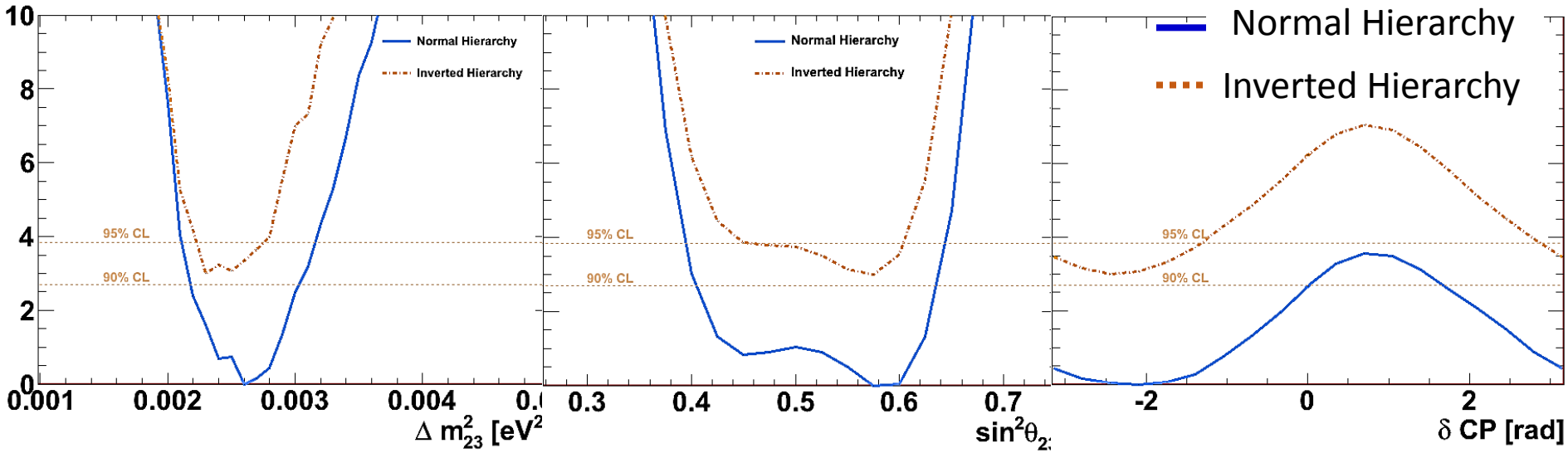
Probability (p-value) of `no $\bar{\nu}_e$ appearance' was evaluated
by generating an ensemble of test experiments
with no $\bar{\nu}_e$ appearance and evaluated log likelihood
for each test experiment, taking into account
variations of oscillation parameters and systematic errors.

'Rate+shape' p-value: 0.335 ~ too few statistics & not conclusive.

Summary

Super-Kamiokande has collected 307.7 kt·yr of atmospheric ν.

ν_τ appearance ~ **3.8 σ** excess (2.7 σ significance expected)



Best fit oscillation parameters	χ^2	δ_{cp}	$\sin^2\theta_{23}$	$\Delta m^2_{23(13)}$ $(x10^{-3})eV^2$
Normal hierarchy	582.4	-2.09 (-0.67π)	0.575	2.6
Inverted hierarchy	585.4	-2.44 (-0.78π)	0.575	2.3

Normal hierarchy is favored slightly ($\Delta\chi^2$ ~ 3.0)
but not statistically significant.

Summary

T2K has accumulated POT is ***11 x 10^{20}*** POT (~ 14% of projected POT)

neutrino running 6.9 x 10^{20} POT

anti-neutrino running 4.0 x 10^{20} POT

- ν_μ disappearance

  Expected # of events without osc. = 446.0 ± 22.5 ($syst.$)

  Observed # of events ***= 120***

ν_μ disappearance	$\sin^2\theta_{23}$	$\Delta m^2_{23(13)}$ ($\times 10^{-3}$ eV^2)
Normal hierarchy	$0.514 \pm^{0.055}_{0.056}$	2.51 ± 0.10
Inverted hierarchy	0.511 ± 0.055	2.48 ± 0.10

- ν_e appearance

  Expected # of background events = 4.9 ± 0.6 ($syst.$)

  Observed # of events ***= 28***

$\sin^2 2\theta_{13}$ = $0.140^{+0.038}_{-0.032}$ (normal hierarchy)

$0.170^{+0.044}_{-0.037}$ (inverted hierarchy)

Summary

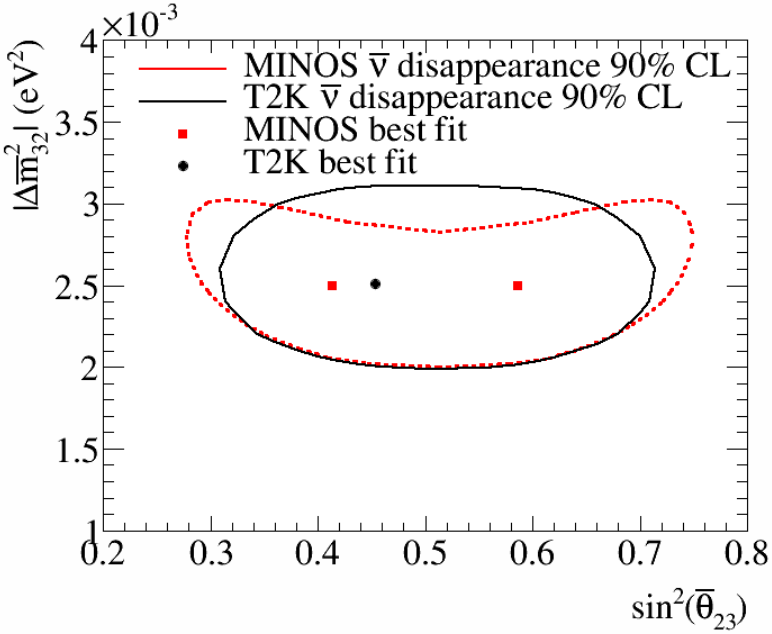
$\bar{\nu}_\mu$ disappearance

Expected # of events without osc. = $103.6 \pm 12.0\ (\ syst.\ )$

Observed # of events ***= 34***

$\sin^2\theta_{23} = 0.45\ ^{+0.24}_{-0.11}$

$\Delta m^2_{23(13)} = 2.51 \pm 0.28 \times 10^{-3}\ eV^2$



$\bar{\nu}_e$ appearance

Expected # of background events

$1.77\ (\ NH\ )\ or\ 1.70\ (\ IH\ )$

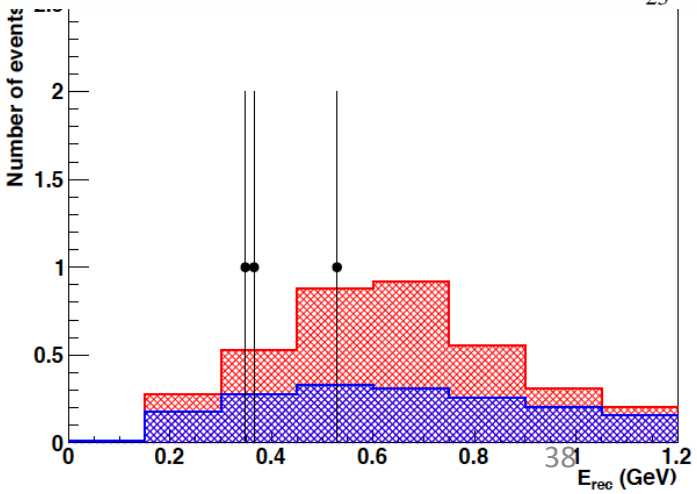
Observed # of events ***= 3***

'Rate+shape' p-value

0.335 for no ν_e appearance

~ too few statistics

& not conclusive yet.



Summary

SK and T2K will continue data taking.

T2K collected just 14 % of projected POT.

~ 1 year goal

~ 9.5 x 10^{20} POT with anti-neutrino mode

(more than twice)

~ 2σ level rejection of no $\bar{\nu}_e$ appearance

~ 60% chance of 99% CL observation

Long term goal (Full stat. = 8 x 10^{21} POT)

Planning to run 50 % ν and 50% $\bar{\nu}$

~ 10 times more statistics in $\bar{\nu}$ mode

May exclude δ_{CP} = 0 at ~ 90% C.L.

fin.

Neutrino oscillation probability ~ ν_μ to ν_e oscillation

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$

θ_{13} Leading term

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

CPV

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2\Delta_{21}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{a\,L}{4E_\nu}(1-2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2S_{13}^2) \cdot \sin^2\Delta_{31},$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E_\nu$$

$$a = 2\sqrt{2}G_F n_e E_\nu$$

For anti neutrinos,

$$a \to -a,\ \delta \to -\delta$$

Now, θ_{13} is known to be (quite) large.

There are chances to observe the contributions from ***mass hierarchy*** and ***CPV (δ)*** !

Solar neutrino observation in SK

Reconstruction of the low energy events

- Energy reconstruction

  Use # of PMT hits

  # of PMT hits ~6hit / MeV

  (SK-I, III, IV)

- Vertex reconstruction

  Use timing of PMT hits

Resolutions

(for 10MeV electrons)

- **Energy** **14%**
- **Vertex** **55cm (SK-III)**

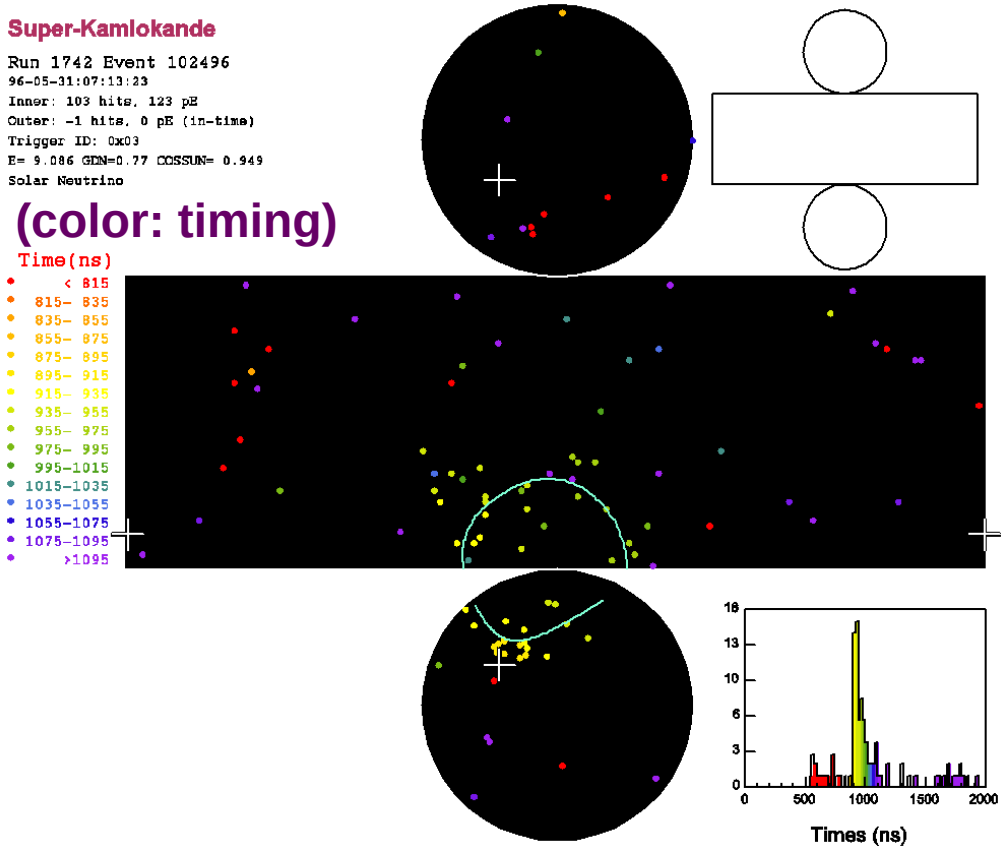
  87cm (SK- I)
- **Direction** **23° (SK-III)**

  26° (SK- I)

(Improved reconstruction was used in the SK-III analysis)

Typical solar ν event candidate

E_e = 9.1MeV, $\cos\theta_{sun}$ = 0.95



Neutrino oscillation studies using atmospheric ν

Changes and Updates to Oscillation Analyses

2166 days of SK-IV data: 4996 days total (307.7 kton·yrs)

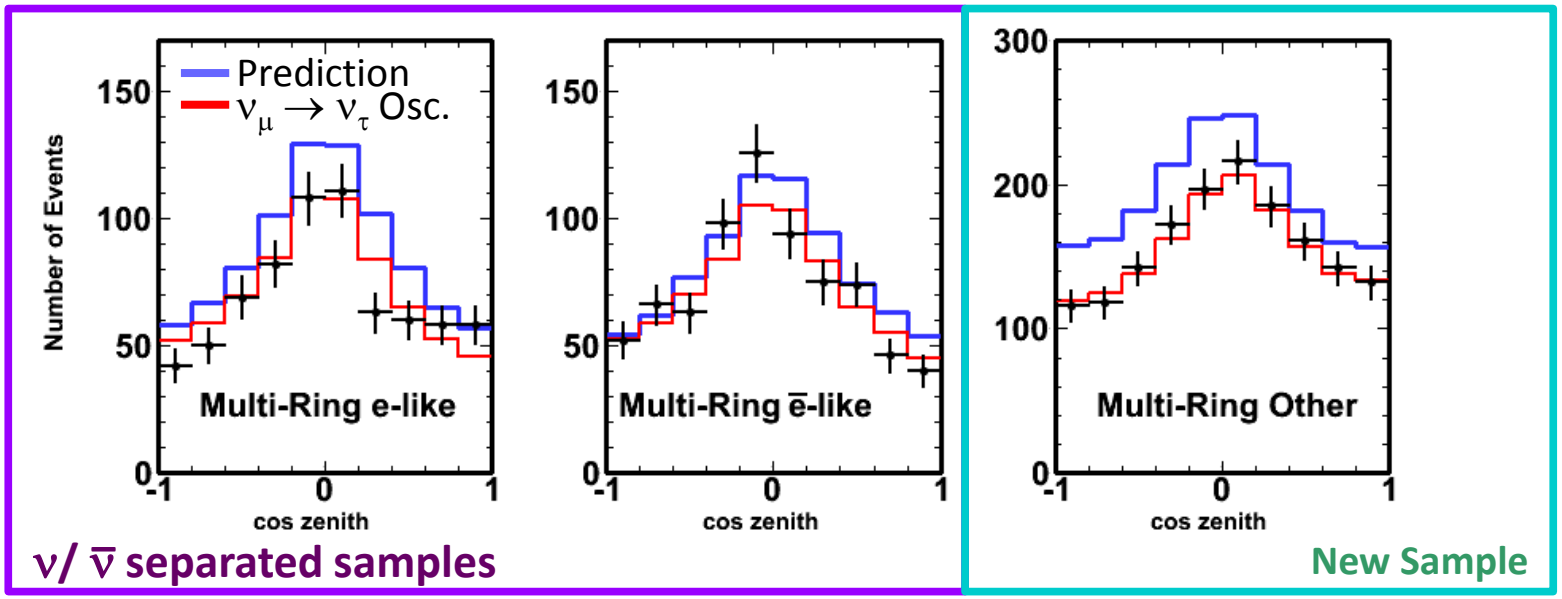
Addition of a new analysis sample

Fully contained Multi-Ring e-like

"other" = not-ν_e & not-$\bar{\nu}_e$

Multi-Ring e-like Sample Purities

Purity	CC ν_e	CCν_μ	CCν_τ	NC
ν-like	72.2%	8.3%	3.2%	16.1%
$\bar{\nu}$-like	75.0%	6.5%	2.8%	15.6%
other	30.9%	33.4%	5.1%	30.5%



Improved systematic error treatments

Updates to cross-section, FSI, detector systematics, 2p-2h (MEC)