Results of T2K

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for T2K collaboration
March 4th 2012

1. Introduction
2. The T2K Experiment
3. Result of $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_x$
   (T2K accumulated 2% of planned data before the earthquake in 11th March 2011)
4. Summary and Outlook

Introduction

- When a neutrino has mass, the weak eigenstate could be different from the mass eigenstate:

Weak eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstate

U_{PMNS} is a 3x3 unitary matrix described by three mixing angles θ_{23}, θ_{13}, θ_{12} and CP-phase δ

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

Introduction

- We have learned a lot about lepton mixing from measurements of neutrino oscillation.

$$\text{cf.}\left|\langle\nu_\beta|\nu_\alpha(t)\rangle\right|^2=\sin^2 2\theta\sin^2(1.27\cdot\Delta m^2\cdot L/E)\ \text{[2flavor case]}$$

$$\theta_{12}=32.7\sim 36.0^\circ$$
$$\theta_{23}=36.8\sim 53.2^\circ$$
$$\theta_{13}<11.4^\circ\qquad \delta_{CP}=?$$

$$U_{PMNS}=\begin{pmatrix} 0.79\sim 0.84 & 0.53\sim 0.59 & <0.20 \\ -0.57\sim -0.19 & 0.39\sim 0.74 & 0.59\sim 0.80 \\ 0.19\sim 0.57 & -0.72\sim -0.42 & 0.59\sim 0.80 \end{pmatrix}$$

- Now we are trying to solve the following two mysteries:
  - U_{PMNS} is very different to U_{CKM}.
    Especially, θ_{23} seems to have a symmetry of "full mixing" and θ_{13} seems to be no mixing.
  - How about δ_{CP}?
    First step for the δ_{CP} quest is the θ_{13} search (equation below).

$$P(\nu_\mu\rightarrow\nu_e)-P(\bar{\nu}_\mu\rightarrow\bar{\nu}_e)\propto\sin\theta_{12}\cdot\sin\underbrace{\theta_{13}}_{\text{Need}\neq 0}\cdot\sin\theta_{23}\cdot\sin\delta$$

T2K(Tokai-to-Kamioka) Experiment

- Search for θ_{13} via the $\nu_\mu \rightarrow \nu_e$ oscillation (appearance)

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\underline{\theta_{13}} \cdot \sin^2 \theta_{23} \cdot \sin^2(1.27 \cdot \Delta m_{32}^2 \cdot L / E)$$

- Precise measurement of θ_{23} & Δm^2_{32} via the $\nu_\mu \rightarrow \nu_x$ oscillation (disappearance)

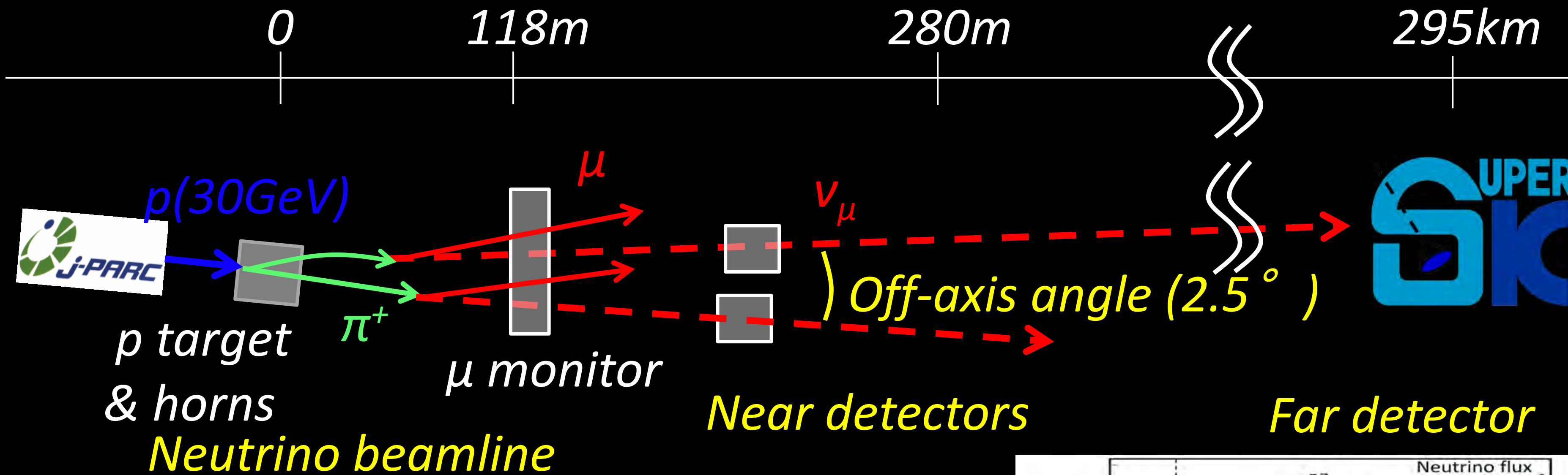
$$P(\nu_\mu \to \nu_x) \cong \sin^2 2\underline{\theta_{23}} \cdot \sin^2(1.27 \cdot \underline{\Delta m_{32}^2} \cdot L / E)$$

T2K Collaboration

~500 collaborators, 59 institutes, 12 countries

T2K Setup

- Three components: Neutrino beamline, Near and Far detectors.

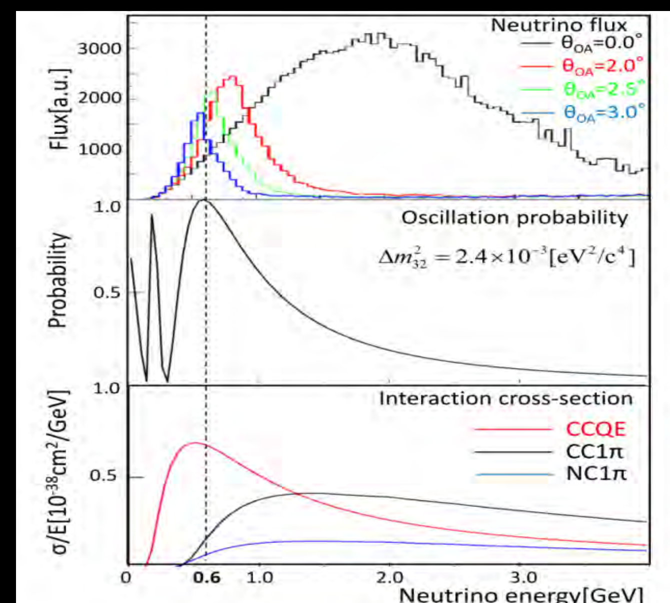


- We employ the off-axis neutrino beam

☺E_ν peak around oscillation maximum

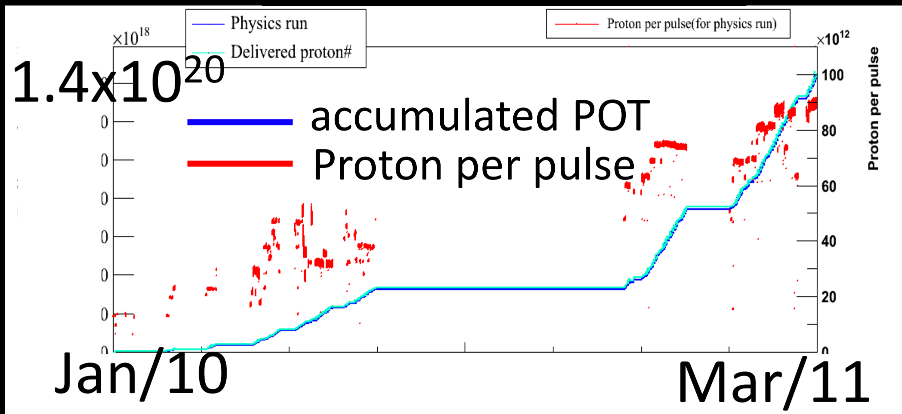
☺reduce background neutrino interactions (CC1π, NC 1π)

E_ν spectrum depends θ_{OA} → need precise control and monitoring of the beam (beam direction of 1mrad ⇒ 2~3% of Ev)



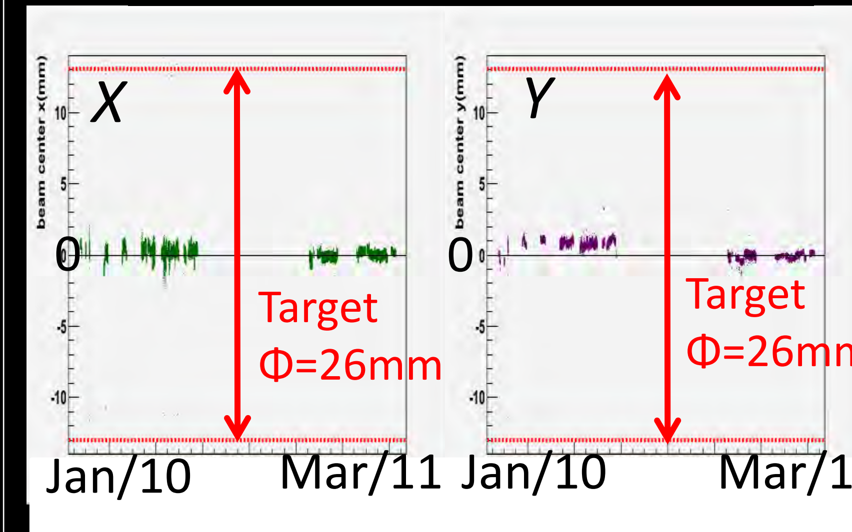
Beam Stability during RUN-I and RUN-II

p beam intensity

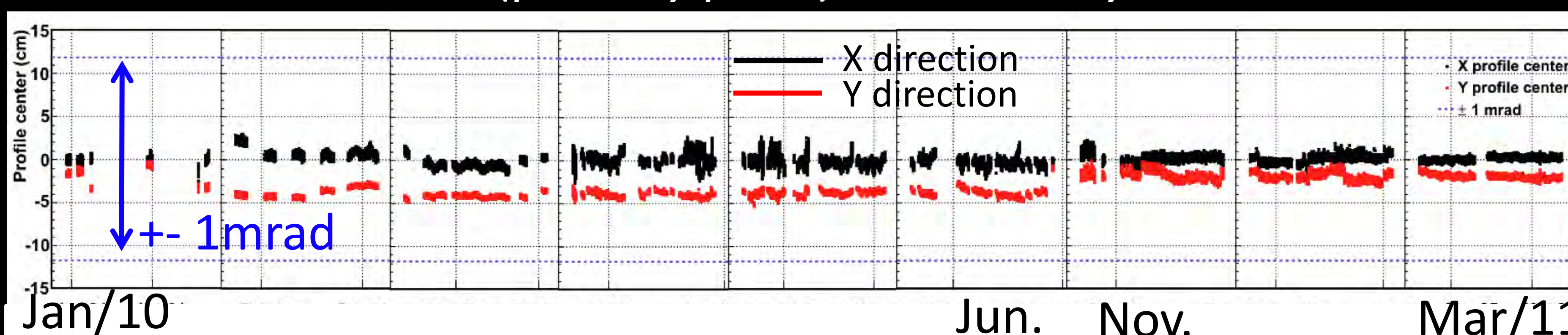


145kW stable operation has been achieved. Total # of POT = 1.4 x 10^{20}

p beam position@target



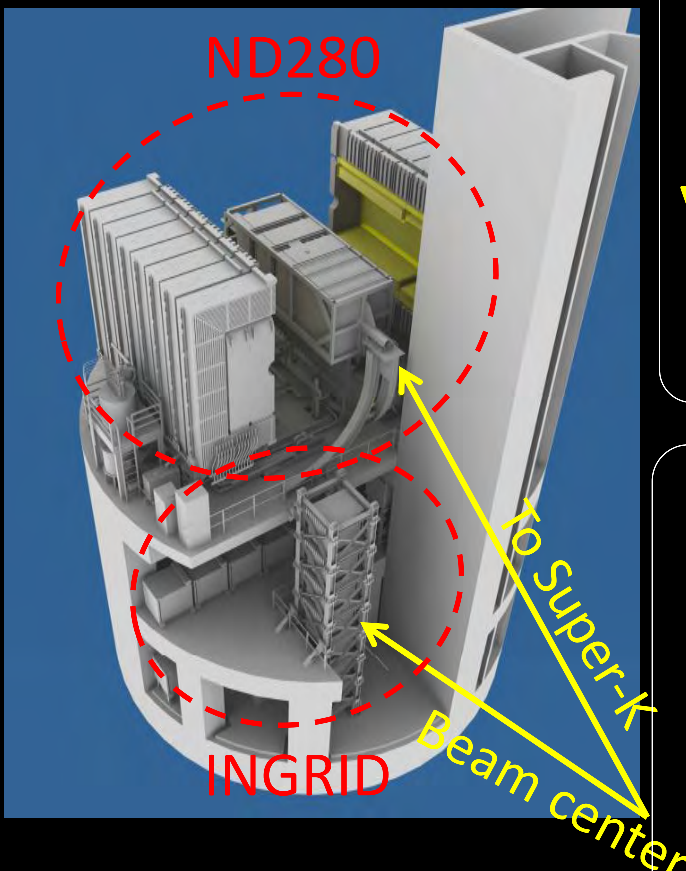
Muon direction (pulse by pulse) measured by muon monitor



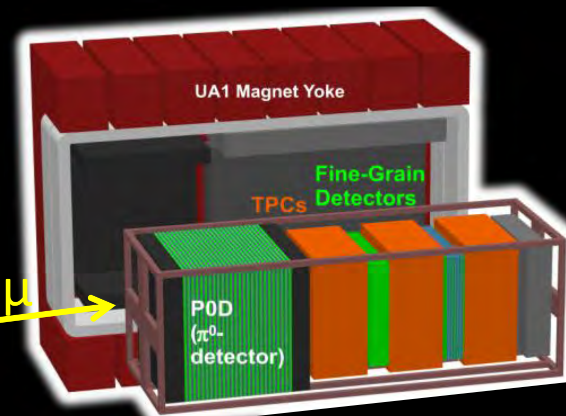
Proton beam and muon is well controlled and stable.

Near Detectors

- Two near detectors are located ~280m downstream from the proton target.



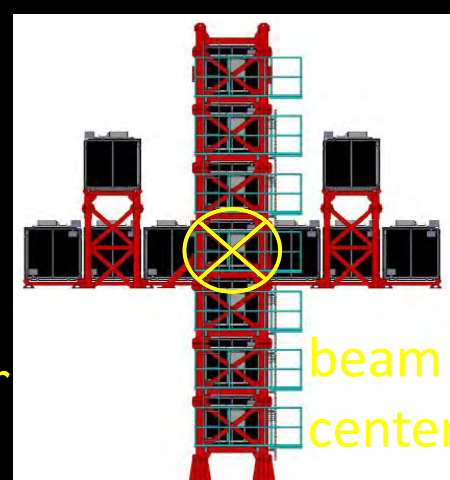
Off-axis detector ND280



Set of detector inside UA1magnet.

Provide ν_μ & ν_e fluxes in this analysis.

On-axis detector INGRID



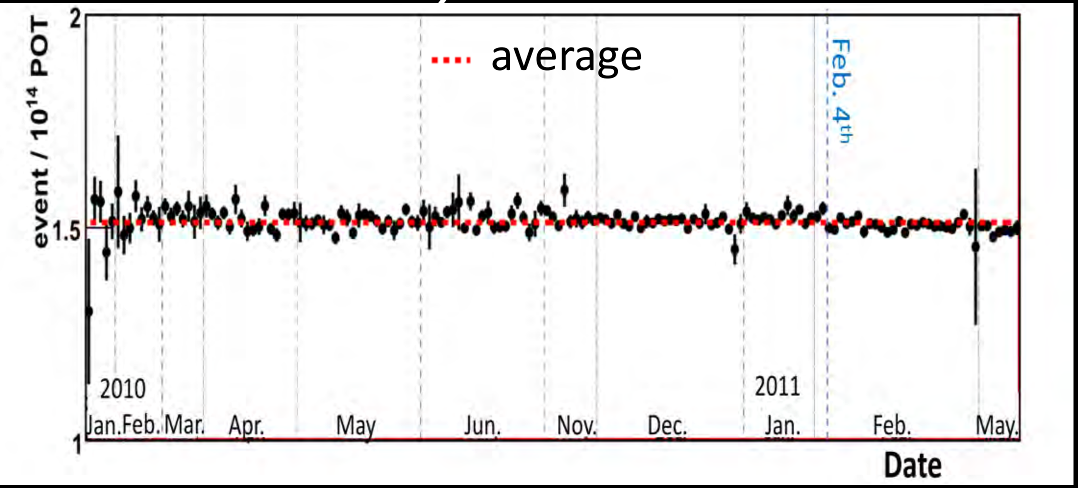
Identical 16 modules covering 10m x 10m.

ν event is counted with each module, ν event rate and direction are monitored.

INGRID measurements *arXiv:1111.3119(2011)*

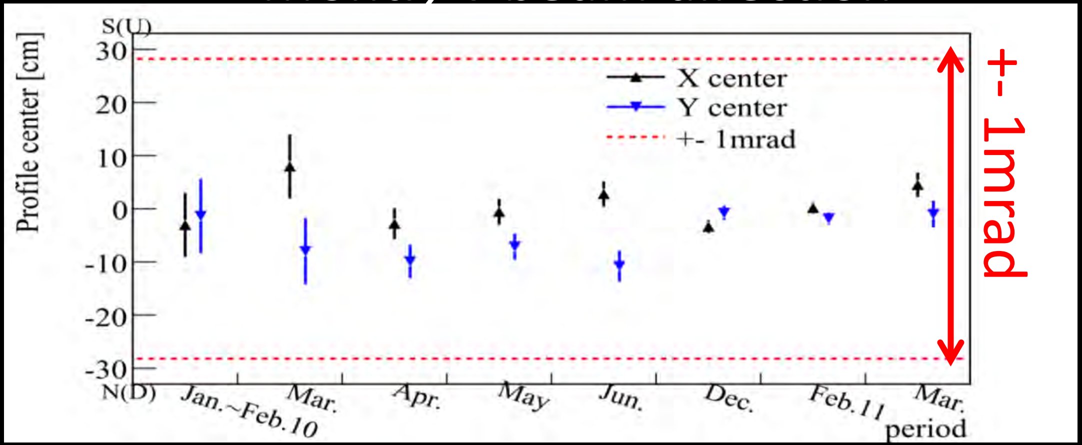
- INGRID took 99.6% of the data and monitored ν event rate/direction

Daily ν event rate



Event rate is stable within statistical error.

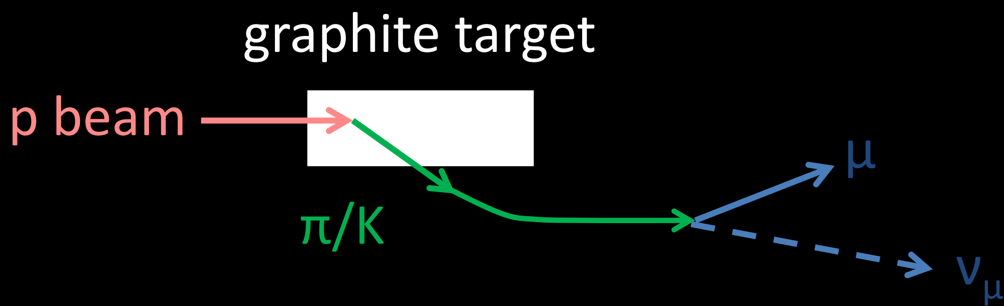
Montly ν beam direction



Neutrino beam direction is stable within our requirement (1mrad)

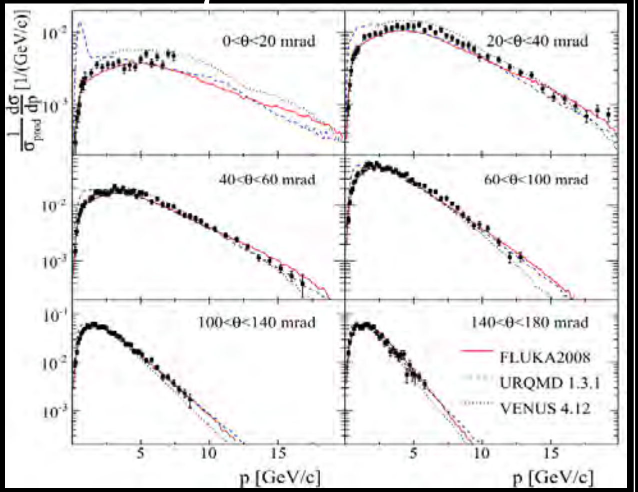
Estimation/Measurement of Neutrino Flux

Estimation of neutrino flux



The estimation is based on the measurement of π/K production in p+Carbon(target) interactions in the NA61 experiment (5-10% errors)

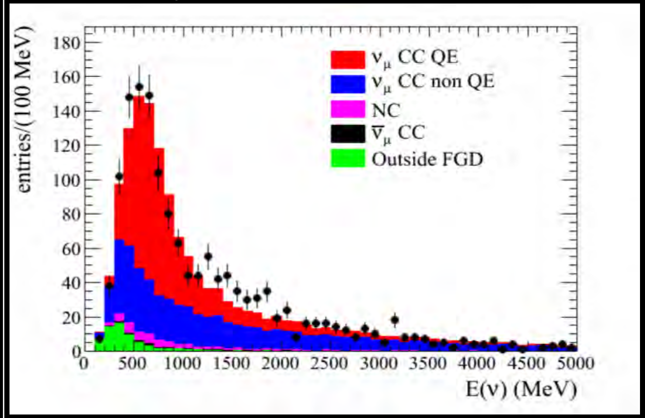
π^+ production



Phys. Rev. C84:034604 (2011)

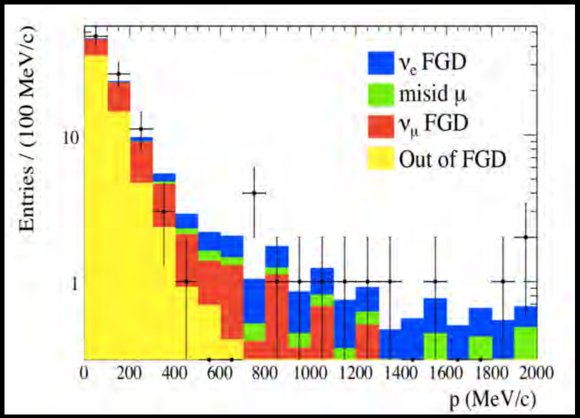
ND280 measurements

ν_μ energy spectrum



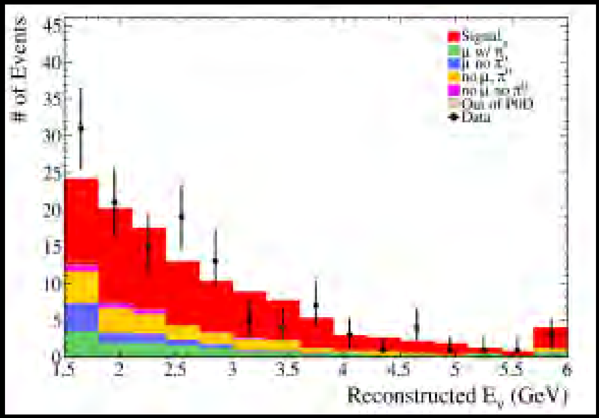
Data/MC = 1.036±0.028(stat.) +0.044-0.037(syst.) ±0.39(phys.)

e momentum with ν_e selection



Data/MC =0.6 ±0.4(stat.)±0.2(syst.)

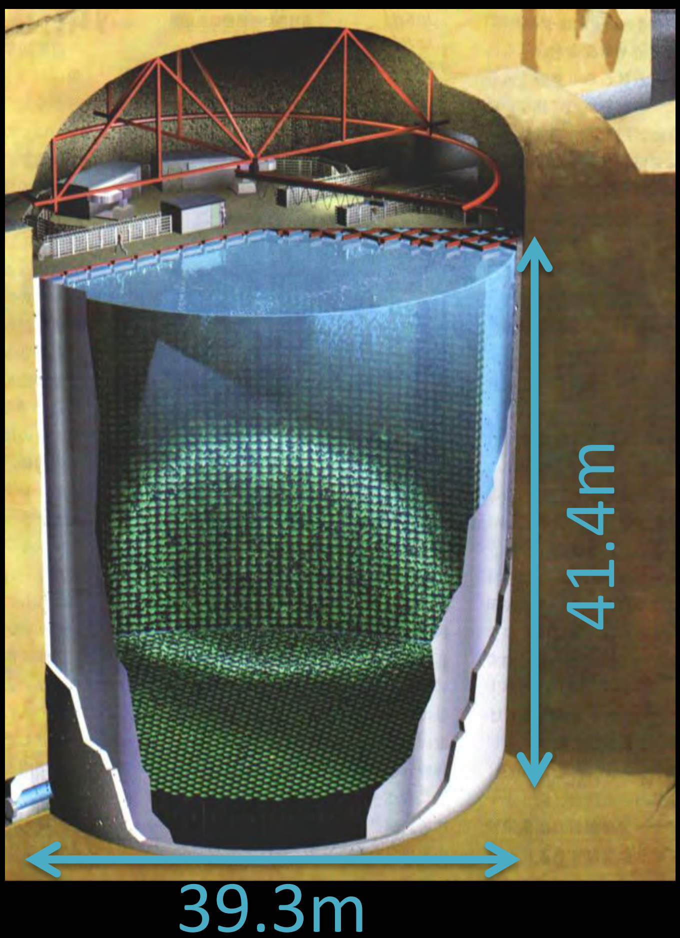
Recon. $E\nu_e$

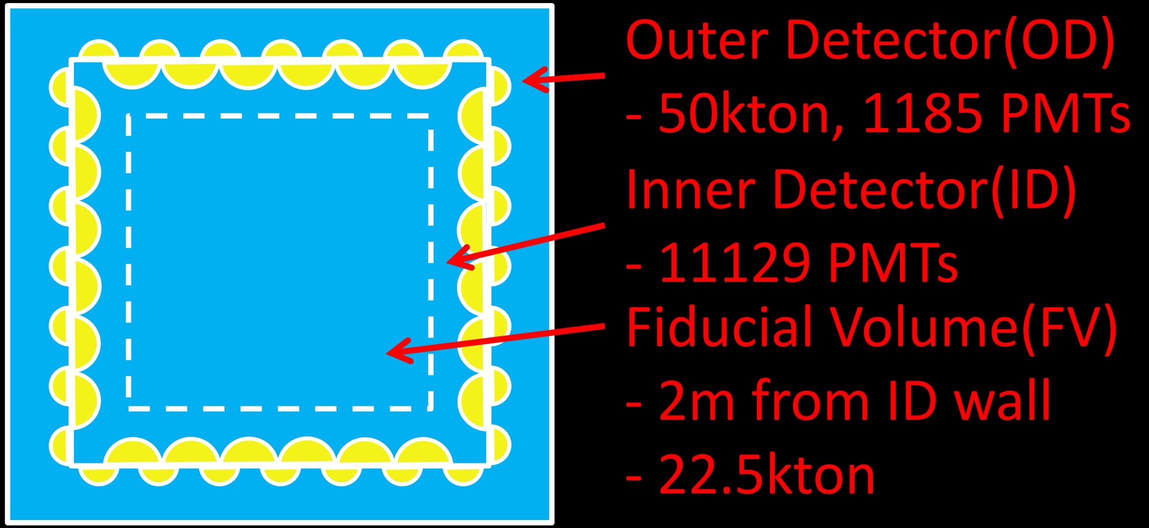


Data/MC =1.19 ±0.15(stat.)±0.26(syst.)

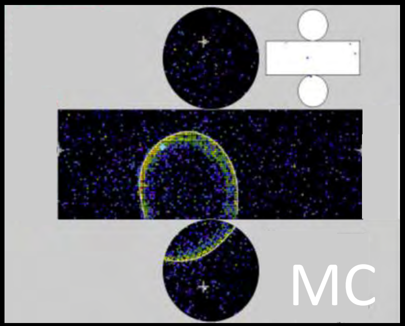
Far Detector Super-K

- Water Cherenkov detector in Kamioka-mine(295km away from J-PARC)
- Record all the hit PMTs within 500 usec from the beam arrival time
- e/μ can be separated by Cherenkov ring pattern and opening angle

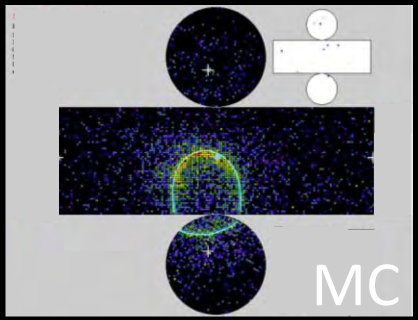




μ-like ring

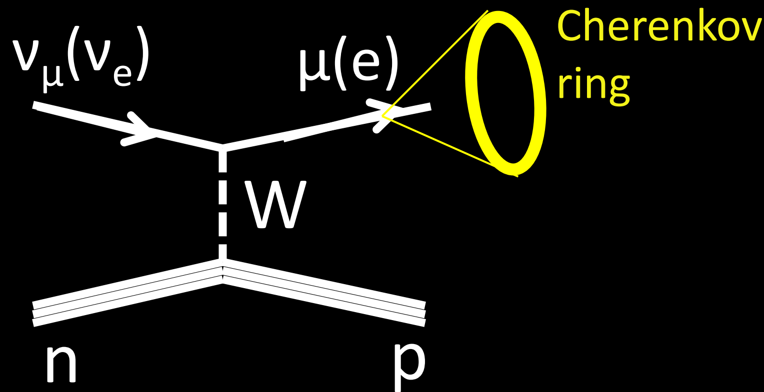


e-like ring

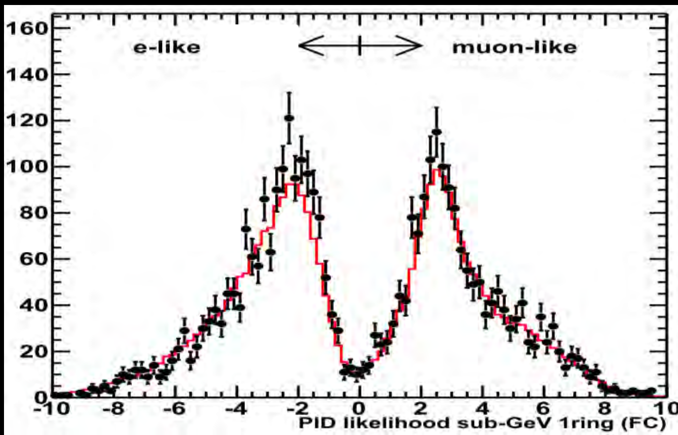


T2K far detector event selection

- Signal : Charged Current Quasi Elastic (CCQE) interaction

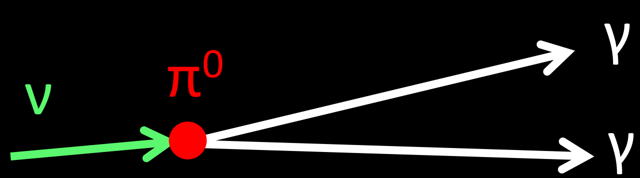


PID likelihood (atm. ν)



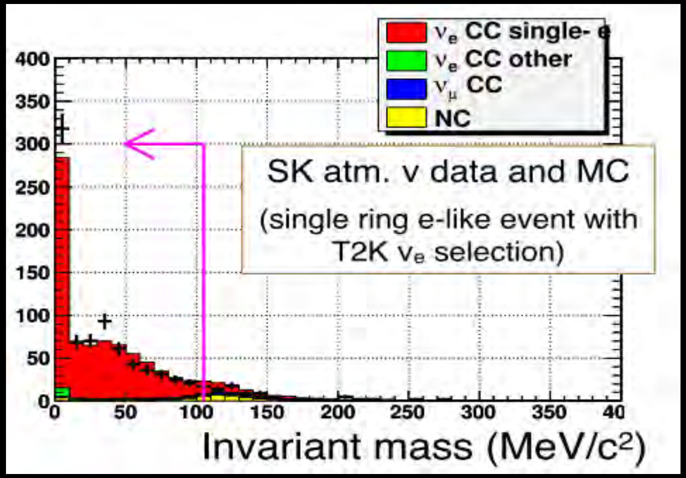
Miss-PID probability ~ 1%

- One of the backgrounds: Neutral Current (NC) π^0 production



Find 2nd shower-ring under 2-ring assumption, and calculate invariant mass

Invariant mass (atm. ν)



Oscillation Analysis Method

Flux prediction

- Proton beam measurement
- Hadron production (NA61 and other external data)

Near detector measurements

- Inclusive CC ν_μ measurement and cross-check of ν_e flux by ND280
- Event rate monitoring by INGRID

Neutrino interactions

- Interaction models
- External cross-section data

Far detector measurements

- Select ν_μ and ν_e CCQE candidates
- Compute N_{MC}^{SK} w/o oscillation
- Adjust normalization with ND280: $N_{exp}^{SK} = (R_\mu^{ND,data}/R_\mu^{ND,MC})\text{x } N_{MC}^{SK}$
- Compare with N_{obs}^{SK} to evaluate oscillation parameters

ν_e analysis → single bin
ν_μ analysis → combining number of events & shape information

Systematic Errors in Oscillation Analysis

	for expected # of BG of ν_e event($\sin^2 2\theta_{13}=0$)		for expected # of ν_μ events ($\sin^2 2\theta_{23}=1$, $\Delta m^2_{32}=2.4\text{x}10^{-3}\text{eV}^2$)	
Error source	**Error[%]**		**Error[%]**	
ν Beam	+8.5	-8.5	+4.8	-4.8
ν cross-section	+9.7	-9.7	+4.9	-4.5
Final state interaction*	+10.1	-10.1	+5.9	-5.9
Super-K	+14.7	-14.7	+10.3	-10.3
ND280 measurement	+6.2	-5.9	+6.1	-5.9
Total	+22.8	-22.7	+15.0	-14.8

*Interaction of pion in nucleus.

Event Selection Result

accumulated data is 2% of aimed statistics

	Data	MC
Fully contained FV at beam timing	88	74.1
Single-ring	41	38.7

ν_e selection

	Data	BG expectation				$\nu_\mu \rightarrow \nu_e$ expect.
		Total	ν_μCC	ν_eCC	NC	
e-like	8	6.6	1.0	1.8	3.7	5.2
E_{vis} > 100 MeV	7	5.7	0.7	1.8	3.2	5.1
No decay-e	6	4.4	0.1	1.5	2.8	4.6
M_{inv} < 105 MeV/c²	6	1.9	0.04	1.1	0.8	4.2
E_ν^{rec} < 1250 MeV	6	1.3	0.03	0.7	0.6	4.1
Efficiency	-	1 %	< 0.1 %	23 %	1 %	66 %

ν_μ selection

	Data	MC w/ 2-flavor oscillation				
		Total	ν_μCCQE	ν_μCC non-QE	ν_eCC	NC
μ-like	33	32.0	17.6	12.4	< 0.1	1.9
P_μ > 200 MeV/c	33	31.8	17.5	12.4	< 0.1	1.9
N(decay-e) ≤ 1	31	28.4	17.3	9.2	< 0.1	1.8
Efficiency	-	20 %	72 %	21 %	0.4 %	3 %

$$\nu_e \text{ event candidates } = 6$$

$$\text{Expectation } (\sin^2 2\theta_{13} = 0, \delta = 0) = 1.5 \pm 0.3$$

$$\text{Expectation } (\sin^2 2\theta_{13} = 0.1, \delta = 0) = 5.5 \pm 1.0$$

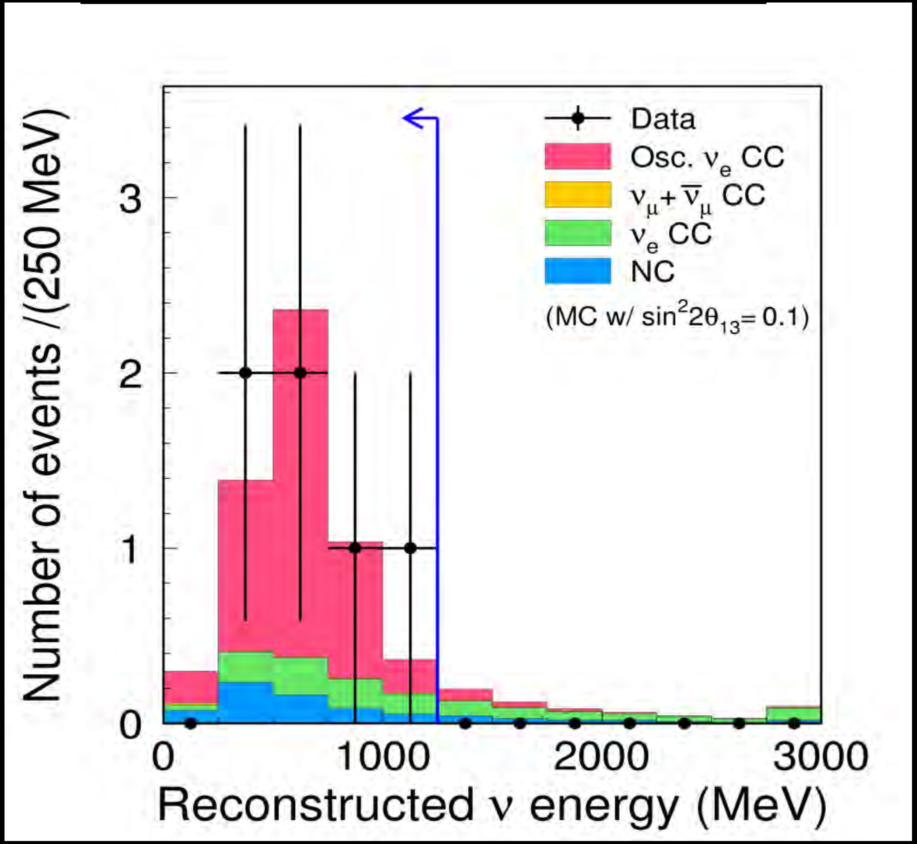
$$\nu_\mu \text{ event candidates } = 31$$

$$\text{Expectation } (\sin^2 2\theta_{23} = 1, \Delta m^2_{32} = 2.4 \times 10^{-3}\,\text{eV}^2) = 28.4^{+4.3}_{-4.2}$$

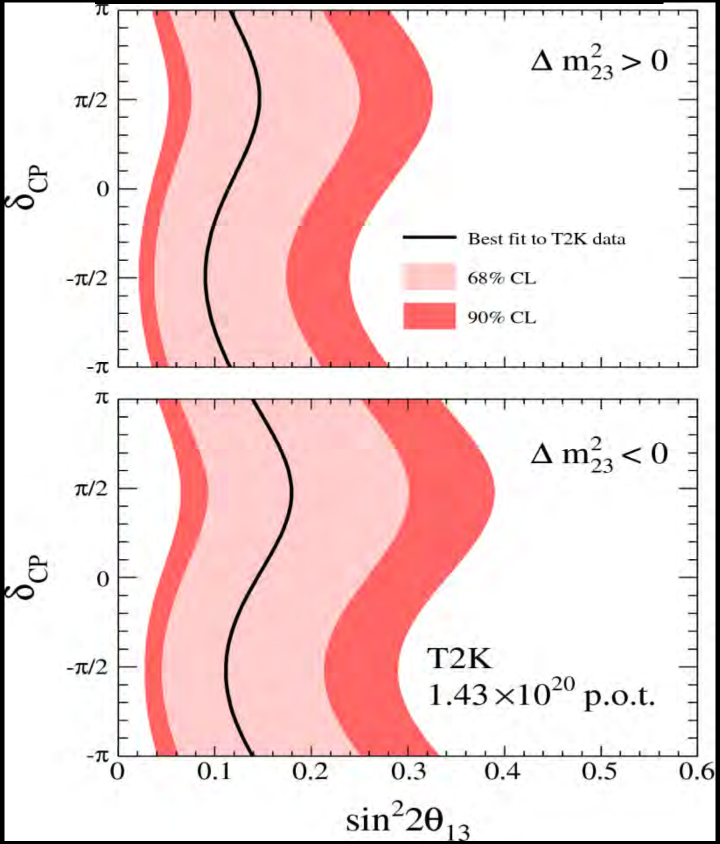
$\nu_\mu \rightarrow \nu_e$ Result

Phys. Rev. Lett. 107:041801, (2011)

Reconstructed ν_e energy



68%/90% CL region



Expected 1.5 ±0.3 BG and observed 6 event. $\theta_{13} = 0$ probability is only 0.7%.

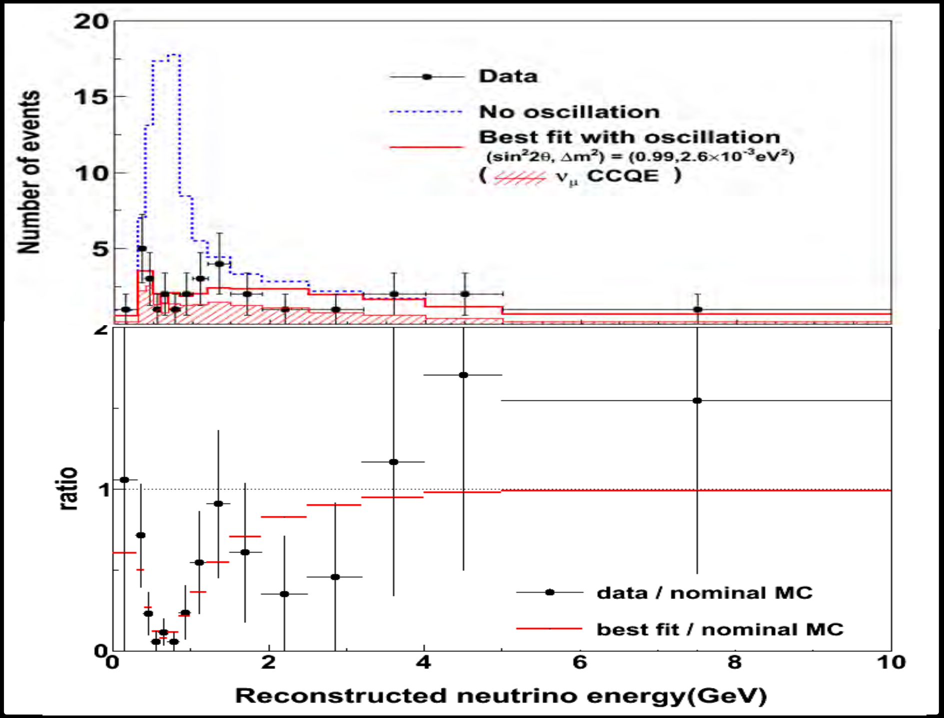
$0.03 < \sin^2 2\theta_{13} < 0.28$(normal)
$0.04 < \sin^2 2\theta_{13} < 0.34$(inverted)

We observed the indication of $\theta_{13} \neq 0$

$\nu_\mu \rightarrow \nu_x$ Result

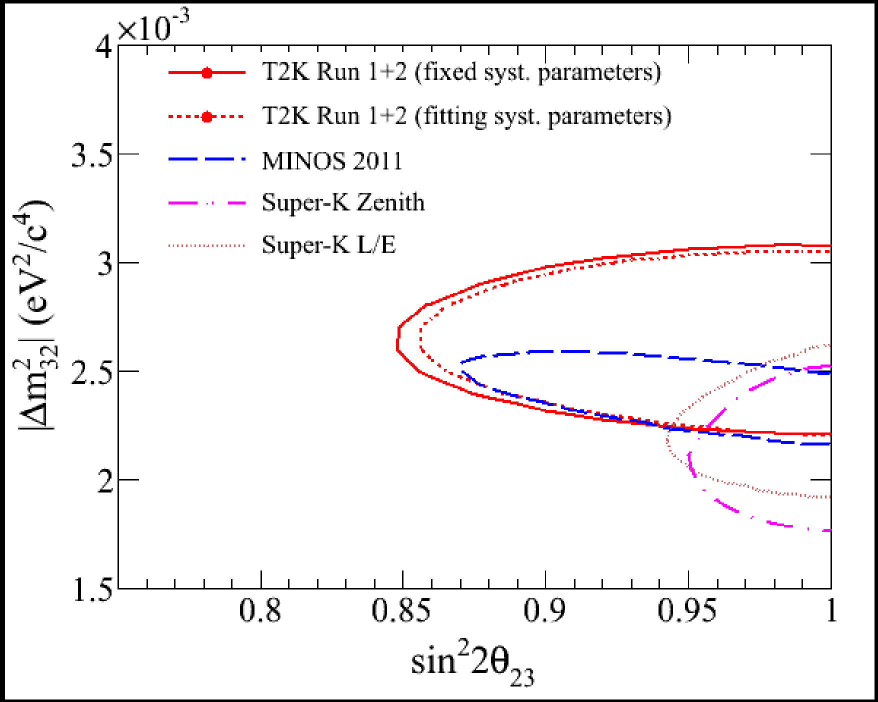
Phys. Rev. D 85, 031103(R)

Reconstructed ν_μ energy



Clear oscillation pattern is observed with off-axis beam

90% CL region



90% CL boundary includes $(1.0,\ 3.1\text{x}10^{-3}\text{eV}^2)$, $(0.84,\ 2.65\text{x}10^{-3}\text{eV}^2)$ and $(1.0,\ 2.2\text{x}10^{-3}\text{eV}^2)$

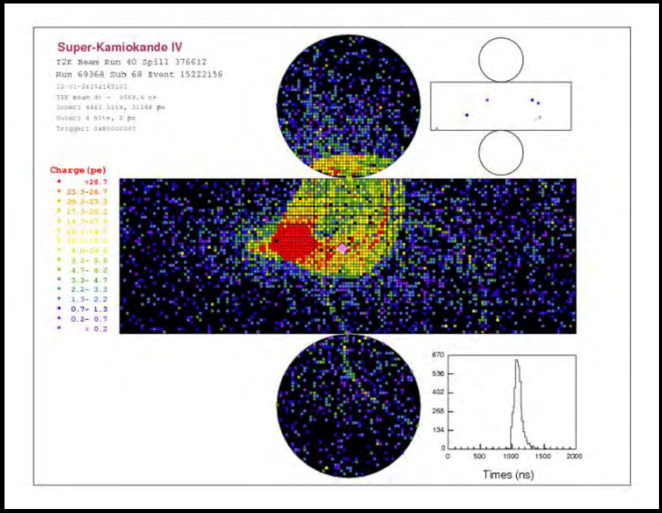
First observation of ν_μ disappearance using off-axis beam.

Summary & Outlook

- We accumulated 2% of the T2K planned data before the earthquake in 11th March 2011
- We obtained the indication of $\theta_{13} \neq 0$ via the $\nu_\mu \rightarrow \nu_e$ appearance.
- We measured $\sin^2 2\theta_{23}$ and Δm^2 precisely via the $\nu_\mu \rightarrow \nu_x$ disappearance.
- We recovered from the earthquake and the T2K beam was back in Dec. 2011.

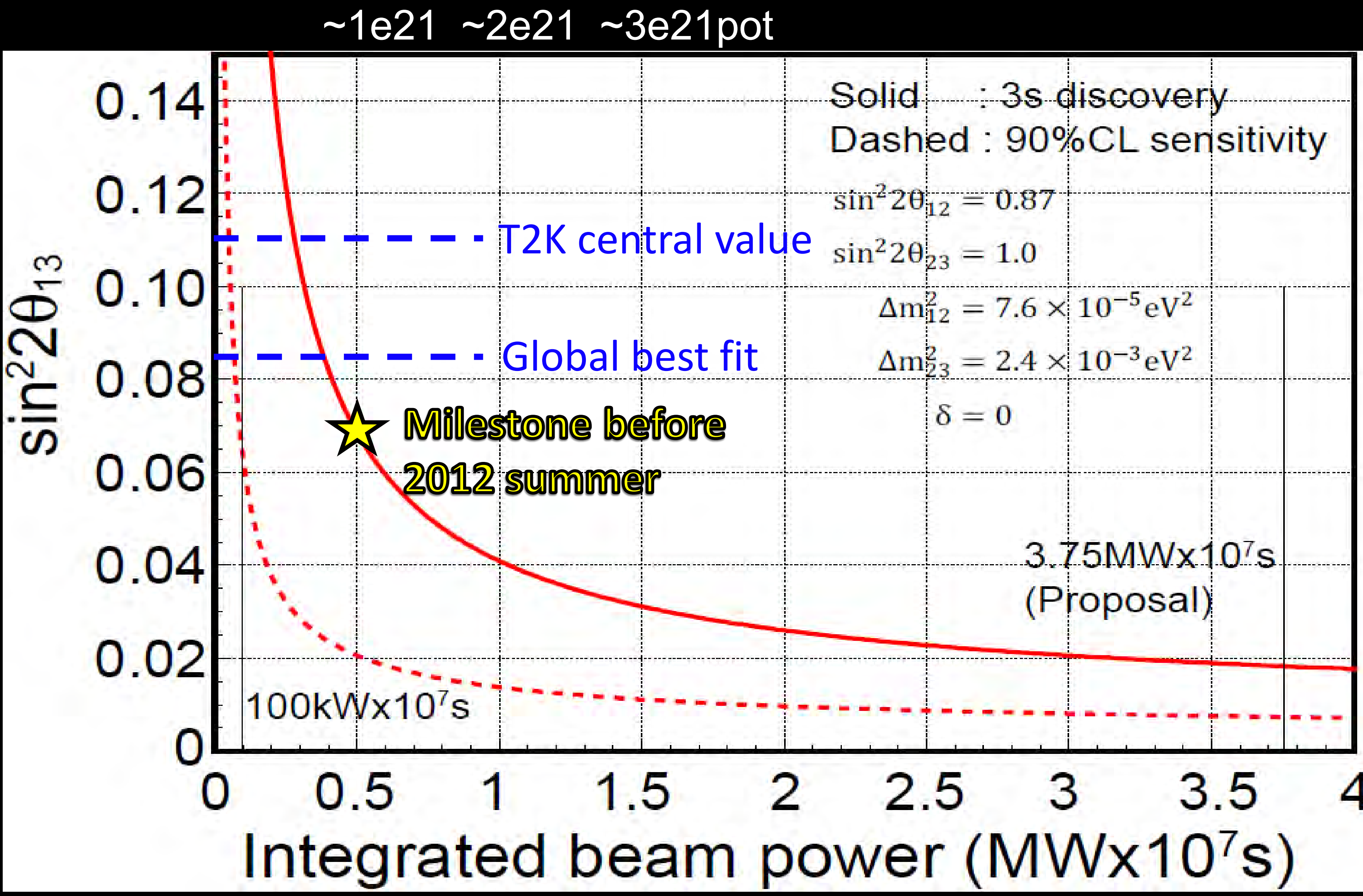
- The T2K experiment resumes from March. The expected beam power is 100 ~ 150 kW.
- Our final goal is to search for $\sin^2 2\theta_{13}$ down to 0.006 and measure $\sin^2 2\theta_{23}$ with a precision of 0.01

First beam ν event since earthquake @Super-K (Jan. 2012)

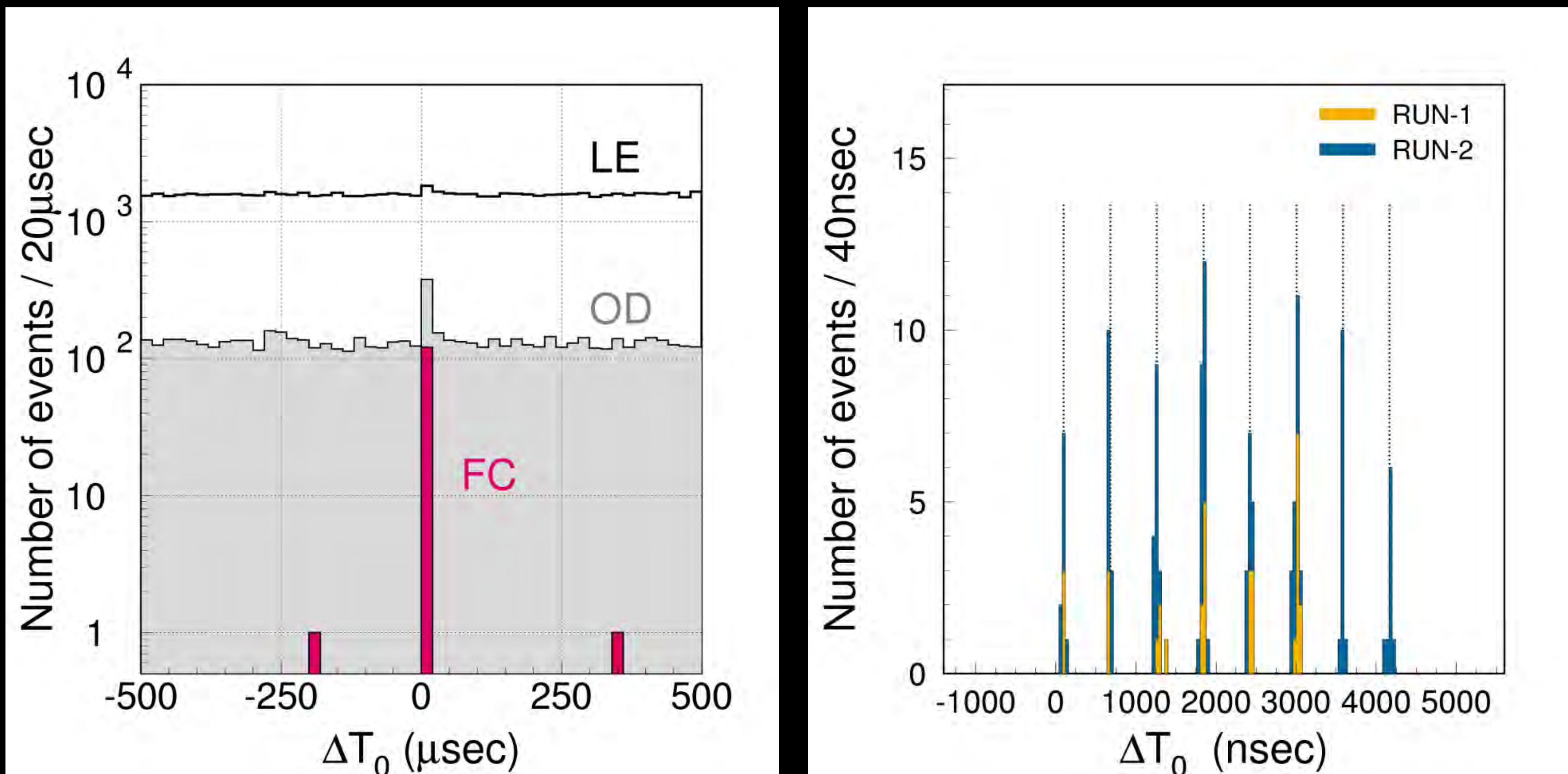


Backup

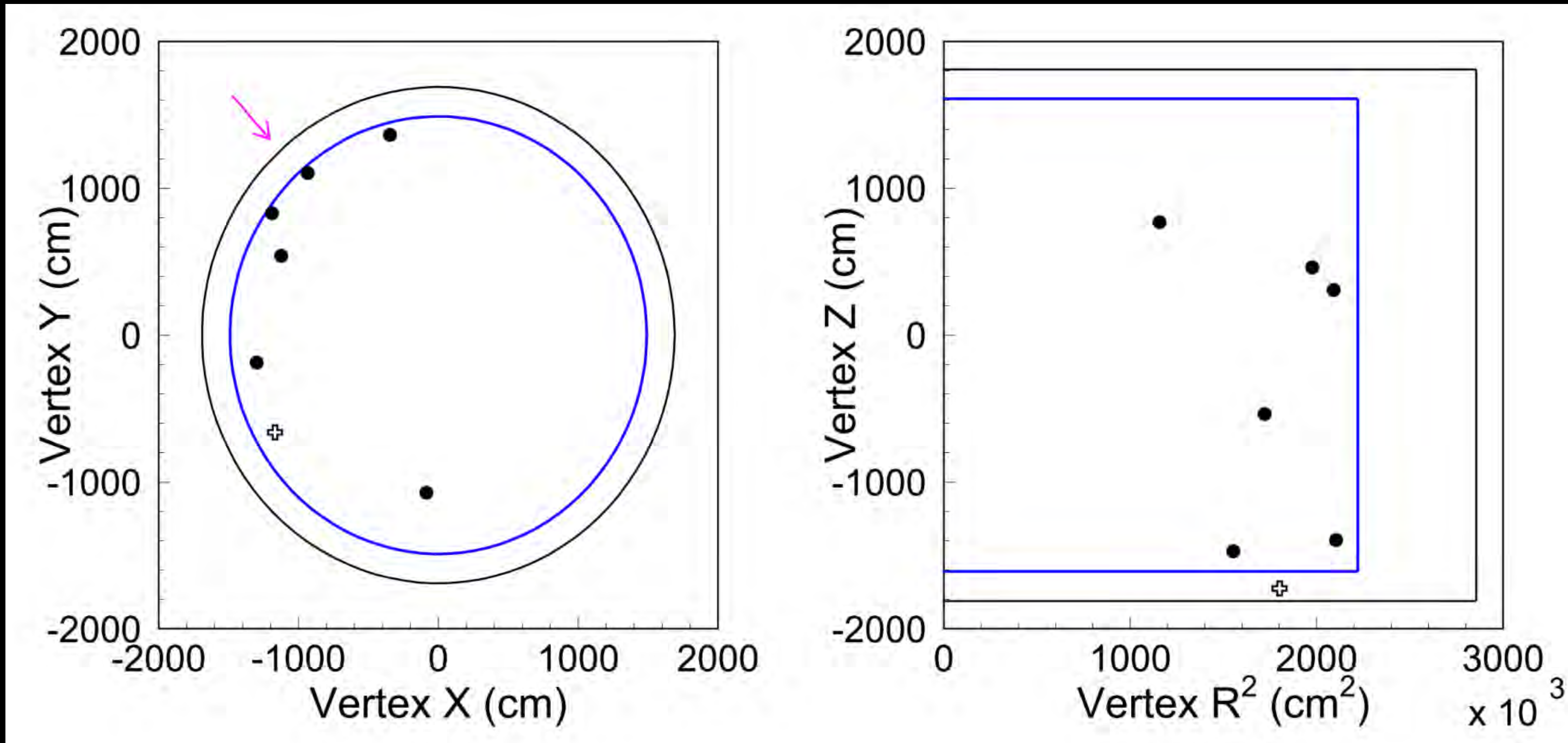
Expected sensitivities for θ_{13}



Event timing @ far detector (Super-K)



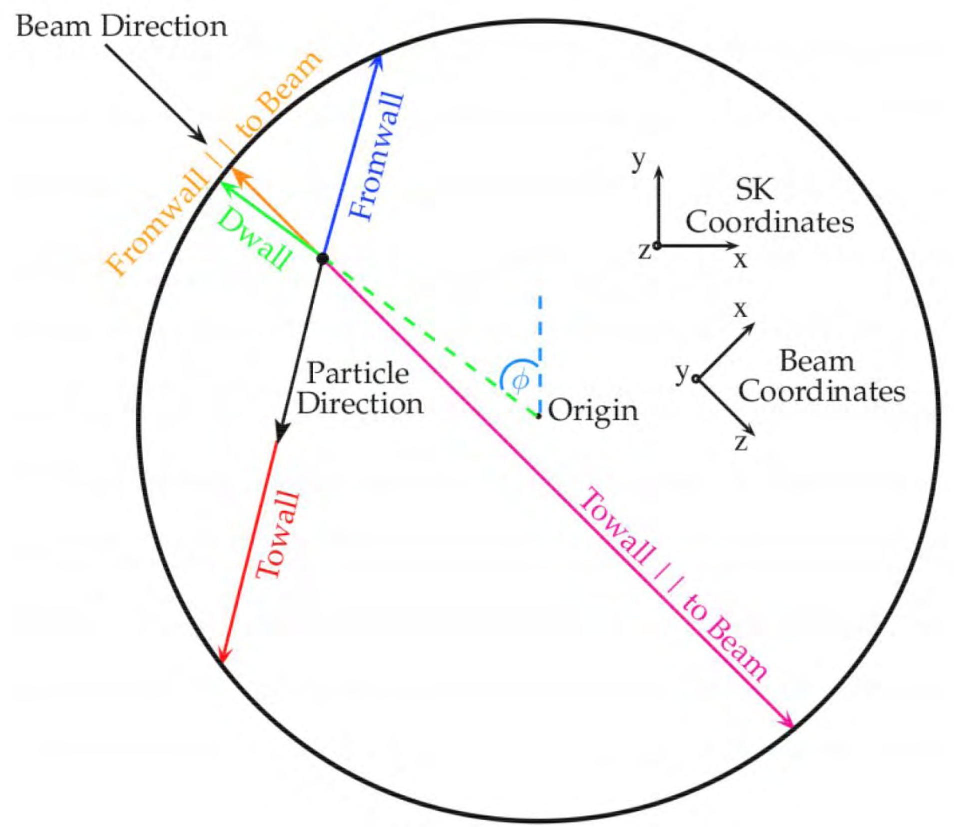
Vertex Distribution of the ν_e candidates



- There is no evidence of the background contamination from outer space such as OD
- The probability to observe the vertex distribution is low, but not unreasonable.

For further investigation, we need more data.

Probability to observe the vertex distribution



Probability From Toy-MC		
Distribution	**7 FC Events**	**6 FCFV Events**
Dwall	22.6%	3.7%
Towall	7.2%	1.9%
Fromwall	22.8%	5.8%
R^2	10.9%	3.1%
Z	38.8%	68.3%
ϕ	28.5%	11.0%

Probability From Toy-MC		
Distribution	**7 FC Events**	**6 FCFV Events**
Towall $\|\|$ *to Beam*	5.1%	1.1%
Fromwall $\|\|$ *to Beam*	1.4%	0.14%
x	32.0%	51.4%
y	42.5%	72.7%
z	5.2%	0.65%