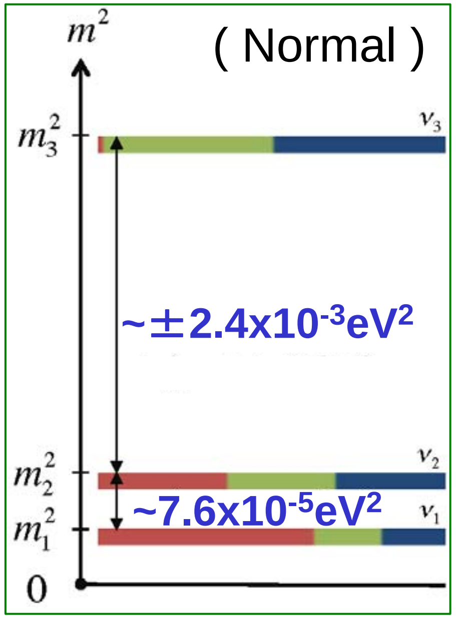
T2K

ICRR / Kamioka obs.
Yoshinari Hayato

Introduction ~ Neutrino oscillation

- 2 mass differences(Δm^2_{12}, Δm^2_{32})
- 3 oscillation angles(θ_{12}, θ_{23}, θ_{13})

& 1 CP phase (δ)



$$|\nu_\alpha\rangle = \Sigma U_{li} |\nu_i\rangle$$

Weak — Mass eigenstates

Maki-**N**akagawa-**S**akata **Matrix ($U_{\alpha i}$)**

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

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

(Atm. + Accl.)

$\sin^2 2\theta_{23}$~1(>0.9)

$|\Delta m^2_{32}|$~2.5x10^{-5}eV^2

(Reactor)

$\sin^2 2\theta_{13} < 0.2$

zero or non zero ?

Unknown **(when T2K planned / started)**

(Solar + Reactor)

$\sin^2\theta_{12}$~0.3

Δm^2_{21}~7.6x10^{-5}eV^2

Tokai to Kamioka long baseline neutrino oscillation experiment (T2K)

Search for the ν_e appearance

→ ***Aim to measure θ_{13}***

(~10 times better sensitivity than previous)

Precision measurements of oscillation parameters with ν_μ disappearance

→ **$\delta(\Delta m^2_{23}) \sim 1\times10^{-4}$ eV^2 , $\delta(\sin^2 2\theta_{23}) \sim 0.01$**

The T2K Collaboration

Host institutes KEK (beam facility and near detectors)
ICRR (Super-Kamiokande)

Canada
- U. Alberta
- U. B. Columbia
- U. Regina
- U. Toronto
- TRIUMF
- U. Victoria
- U. Winnipeg
- York U.

France
- CEA Saclay
- IPN Lyon
- LLR E. Poly.
- LPNHE Paris

Germany
- U. Aachen

Italy
- INFN, U. Bari
- INFN, U. Napoli
- INFN, U. Padova
- INFN, U. Roma

Japan
- ICRR Kamioka
- KEK
- Kobe U.
- Kyoto U.
- Miyagi U. Edu.
- Osaka City U.
- U. Tokyo

Poland
- NCBJ, Warsaw
- IFJ PAN, Kracow
- U. Silesia, Katowice
- T. U. Warsaw
- U. Warsaw
- U. Wroclaw

Russia
- INR

S. Korea
- N. U. Chonnam
- U. Dongshin
- N. U. Seoul

Spain
- IFIC, Valencia
- U. A. Barcelona

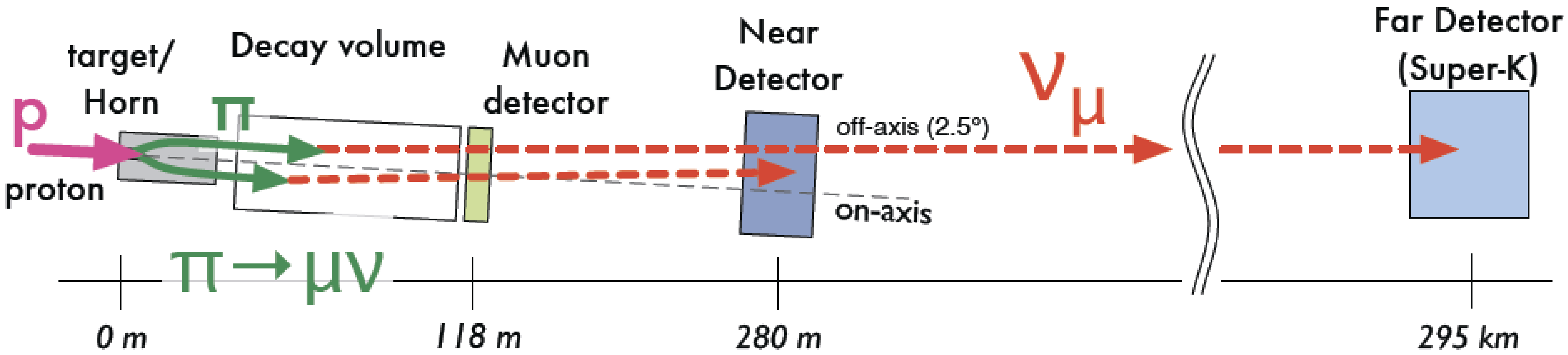
Switzerland
- ETH Zurich
- U. Bern
- U. Geneva

UK
- Imperial C. L.
- Lancaster U.
- Liverpool U.
- Queen Mary U. L.
- Oxford U.
- Sheffield U.
- STFC/RAL
- STFC/Daresbury
- Warwick U.

USA
- Boston U.
- Colorado S. U.
- U. Colorado
- Duke U.
- U. C. Irvine
- Louisiana S. U.
- U. Pittsburgh
- U. Rochester
- Stony Brook U.
- U. Washington

Total:
~500 members
57 institutes
12 countries

T2K ~ Schematic diagram of the experiment



3 major components

1. Accelerator, neutrino beam line & beam monitors

   Produce neutrino beam
   and monitor primary and secondary particles

2. Neutrino detectors in the near site

   Measure produced neutrino beam before oscillation
   ~ measure yield, energy spectrum, flavor ratio
   ~ study neutrino interactions

(1. and 2.: Tokai)

3. Neutrino detector (SK) at far site ~ Kamioka

   Measure oscillated neutrino beam
   and determine neutrino oscillation parameters

T2K neutrino beam ~ Off axis beam ~

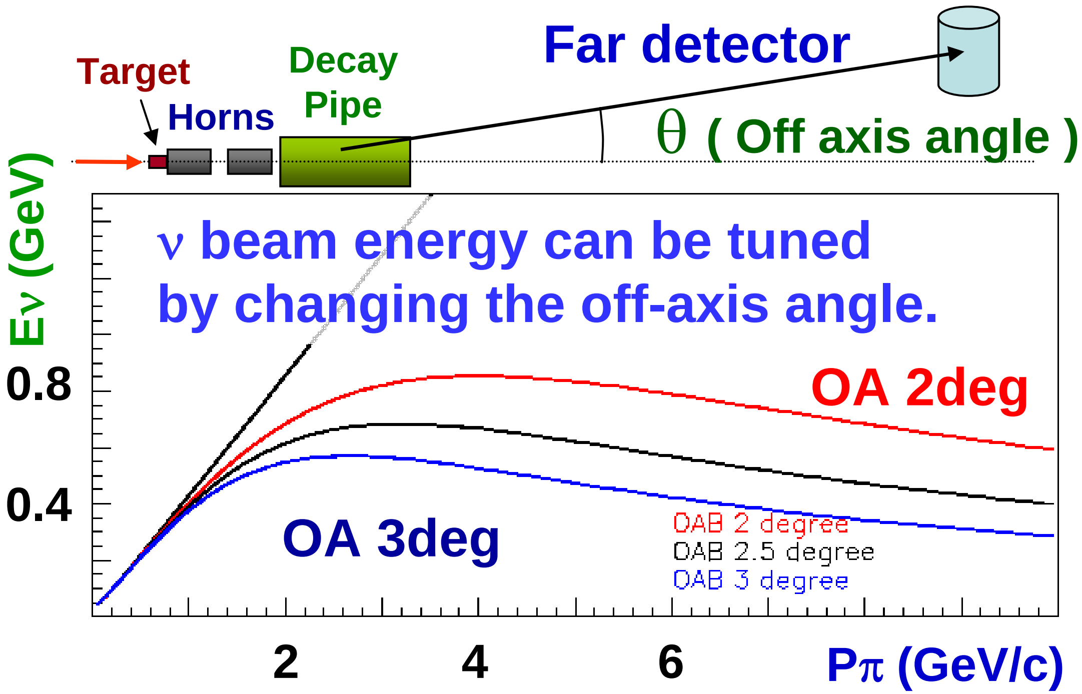
Maximize sensitivity in oscillation studies

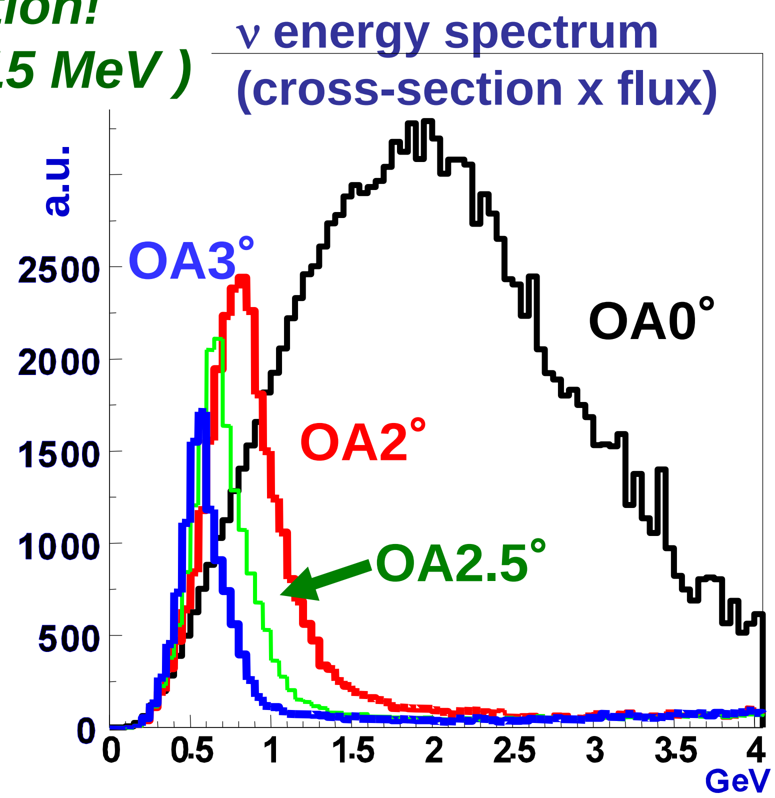
➡ Use narrow band beam with peak energy at the oscillation maximum

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

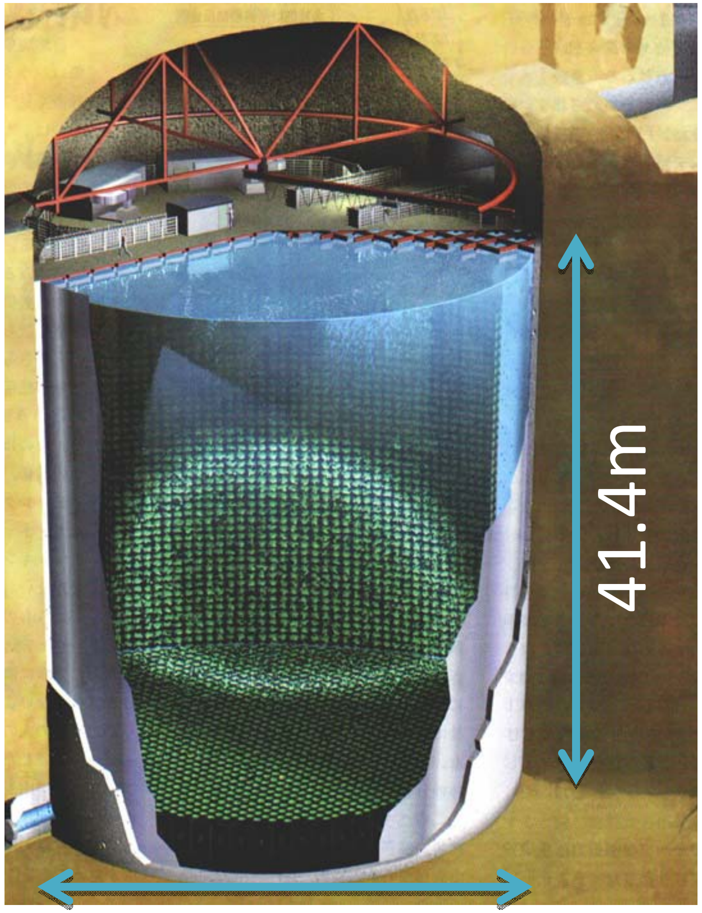
- Quasi-monochromatic beam ~ suppressed high energy ν
- Energy is tunable (Change off axis angle)

Important to monitor beam direction!
(1mrad ~ peak E_ν shifts by ~15 MeV)



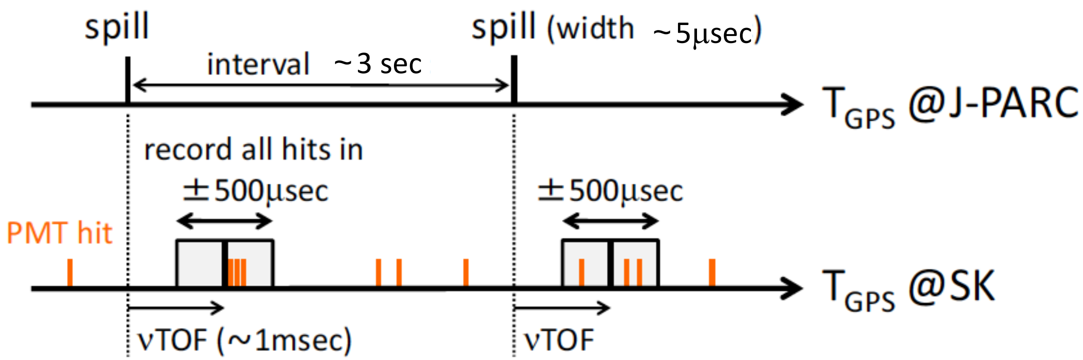


T2K far detector ~ Super-Kamiokande



- New DAQ system installed in 2008
- Recording of all PMT hits within ±500μsec of each ν beam arrival timing in SK using GPS.
- 2 independent GPS system
- Additional special GPS receiver

  To monitor the "GPS time" difference between Tokai and Kamioka.

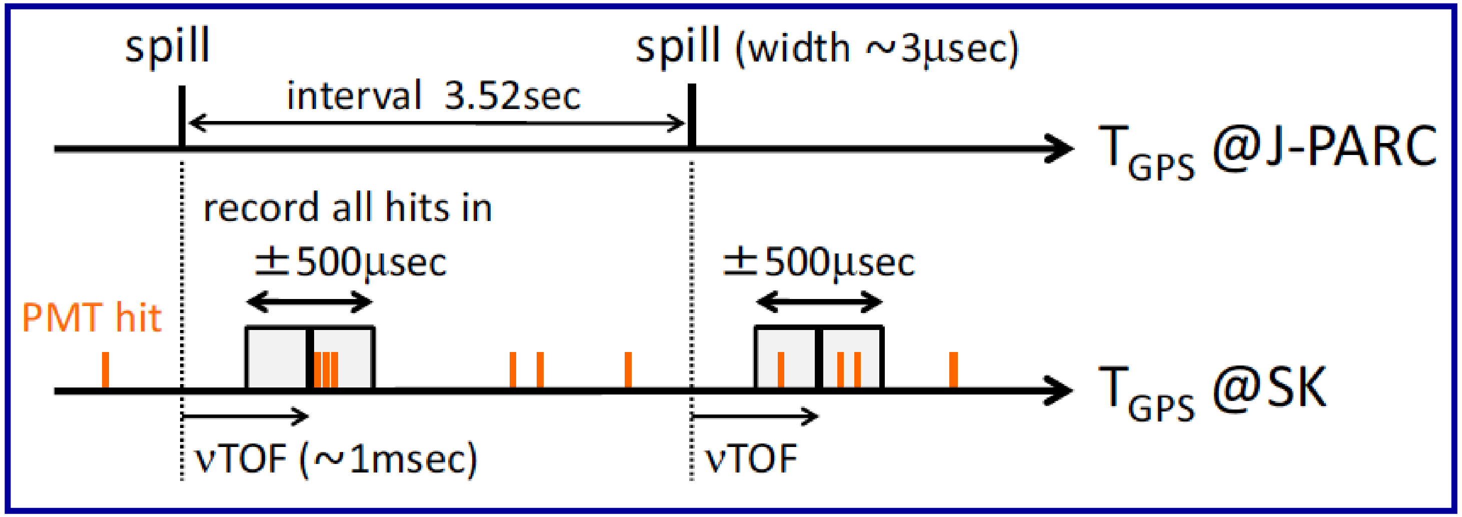


Contributions from SK (ICRR)

1) Collect T2K neutrino beam data using SK

Dedicated trigger system (triggering scheme)

to collect all the PMT hits around the T2K ν beam



Monitor the status of the system (GPS, DAQ, detector)

Keep the live time ratio as high as possible.

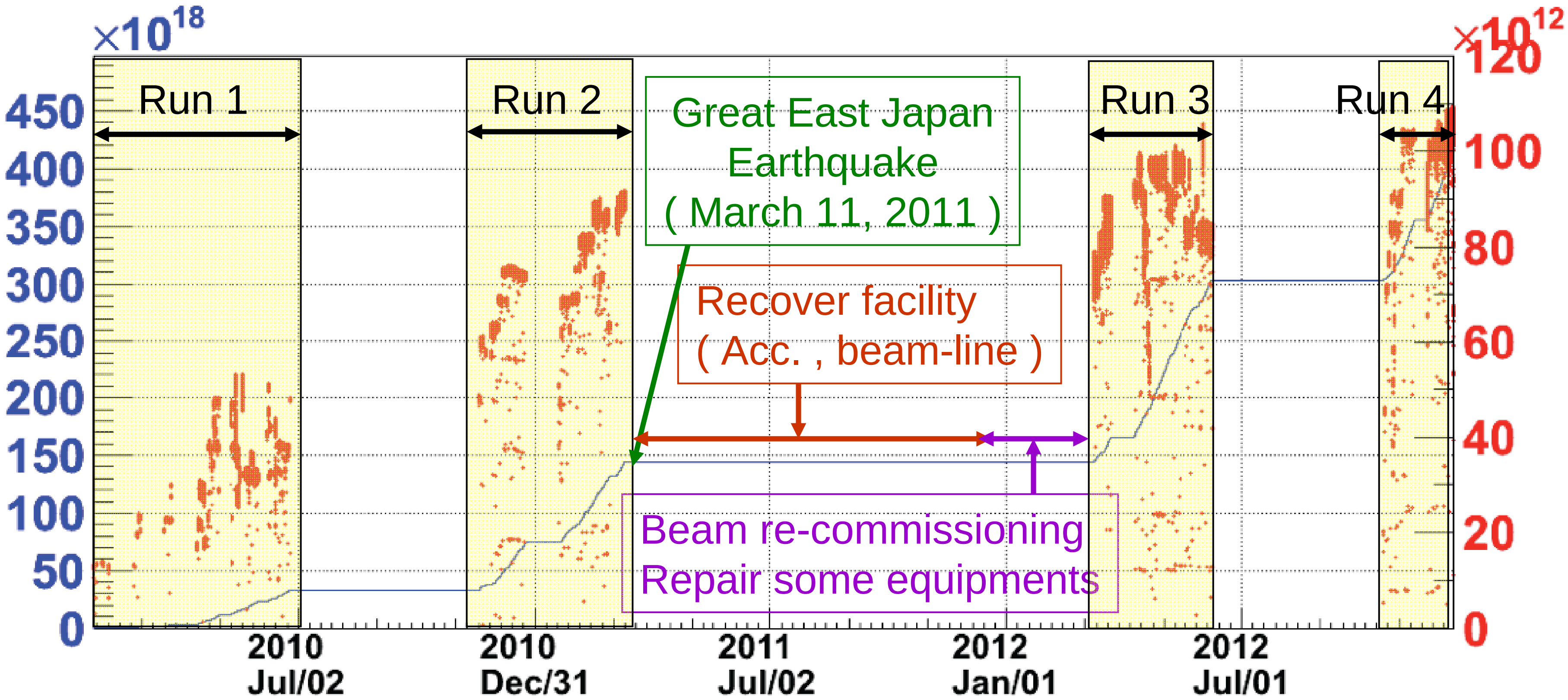
SK DAQ live-time efficiency during the T2K beam time

~ 99.2 %

(Careful arrangements of calibration and maintenance works in SK with the beam line / accelerator groups)

T2K neutrino beam history and status

The T2K experiment started physics data taking in Jan. 2010.



- Beam power reached at 210kW in Dec. 2012.
- Delivered number of protons : 4.2 x 10^{20} protons on target (~ 5 % of requested beam)

Contributions from SK (ICRR)

2) Provide T2K neutrino beam event data

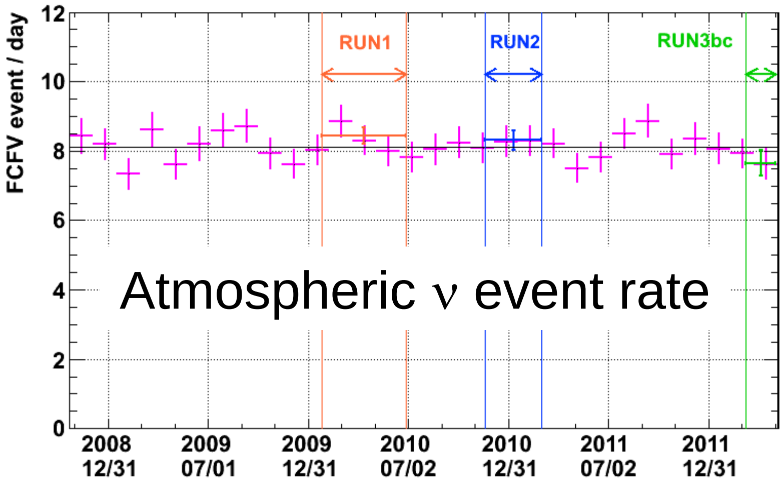
Define “T2K beam neutrino event” selection criteria

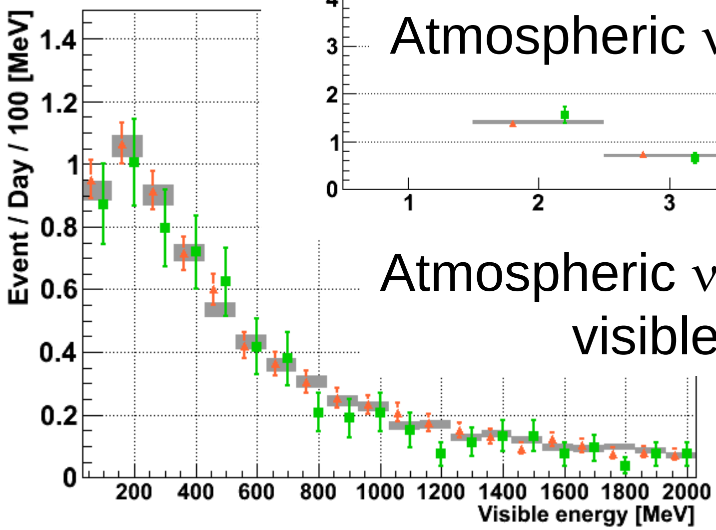
(kind of higher-level software trigger)

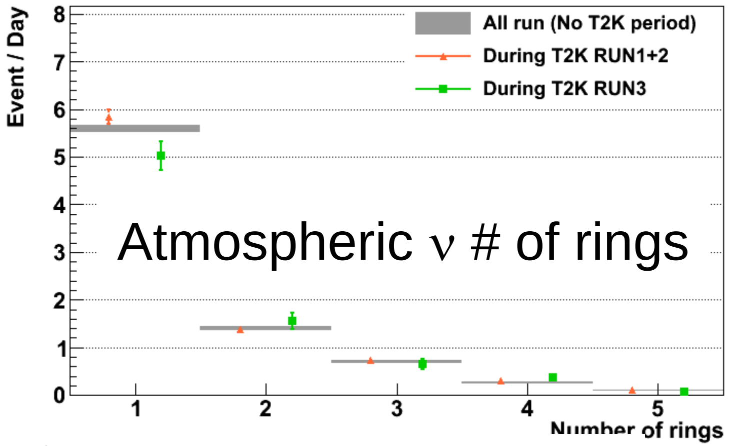
Monitor the quality of the data

Using atmospheric ν events, calibration data etc..

Some example of the stability plots from atmospheric ν data







Contributions from SK (ICRR)

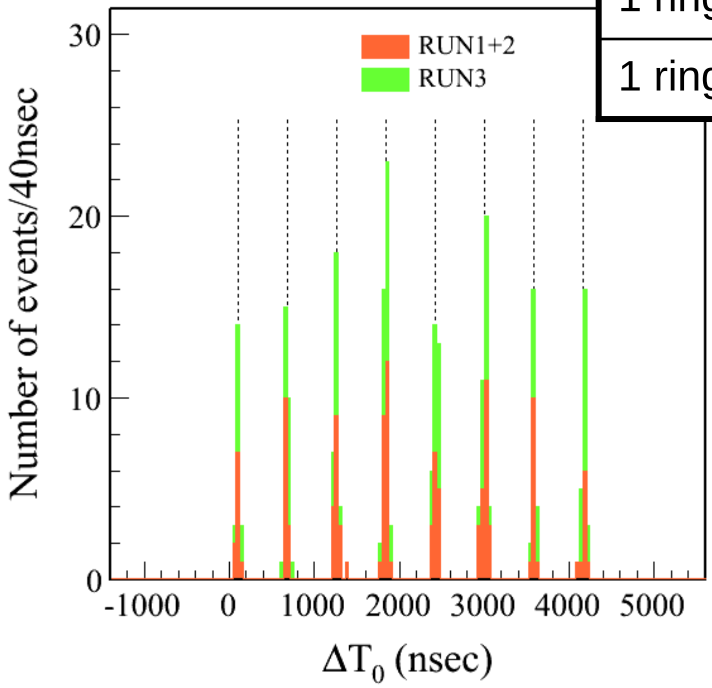
2) Provide T2K neutrino beam event data

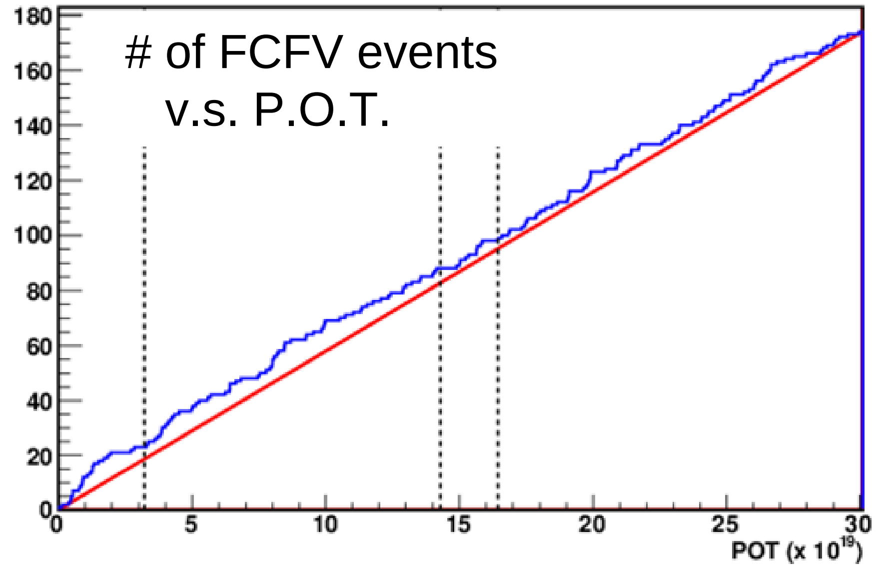
Make DST applying the T2K ν event selection criteria

Event summary
(Spring '10
~ Summer '12)

	Data	Monte Carlo simulation			
		$Sin^2\theta_{13}$=0.1	$Sin^2\theta_{13}$=0	No Osc.	B.G.
FC	240	231.6	216.4	465.8	0.039
FCFV	174	163.4	152.7	322.0	0.048
Single Ring	88	85.6	76.5	222.7	
1 ring μ-like	66	61.8	61.8	201.4	
1 ring e-like	22	23.8	14.7	21.4	

Beam timing structure
observed in SK





Contributions from SK (ICRR)

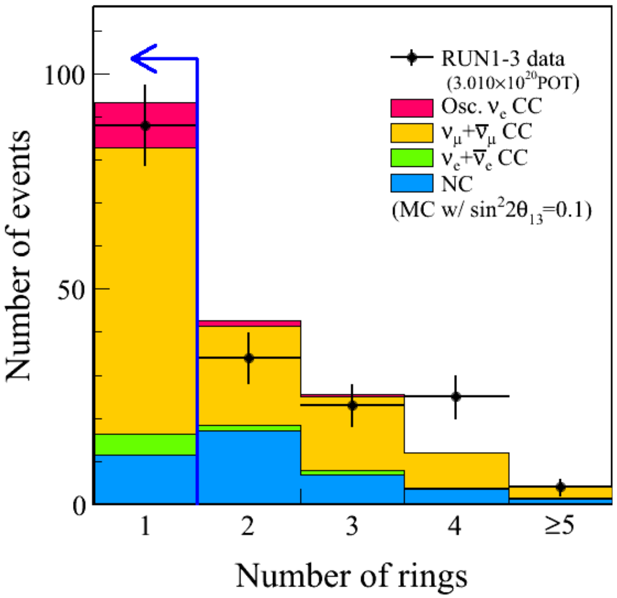
3) Provide reconstruction tools

Based on the event reconstruction tools
developed for the atmospheric neutrino analyses.

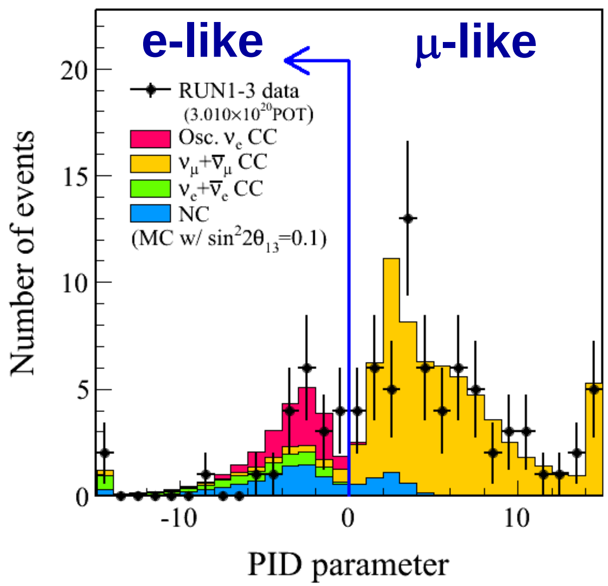
Optimize for the T2K neutrino oscillation analyses
Energy range, target neutrino interactions.
example) π^0 rejection for ν_e appearance

example plots of the results of the reconstruction

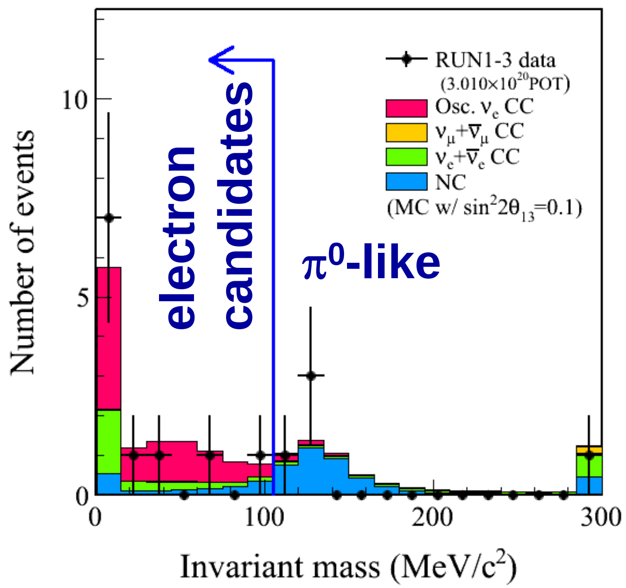
# of rings



Particle ID



π^0 rejection



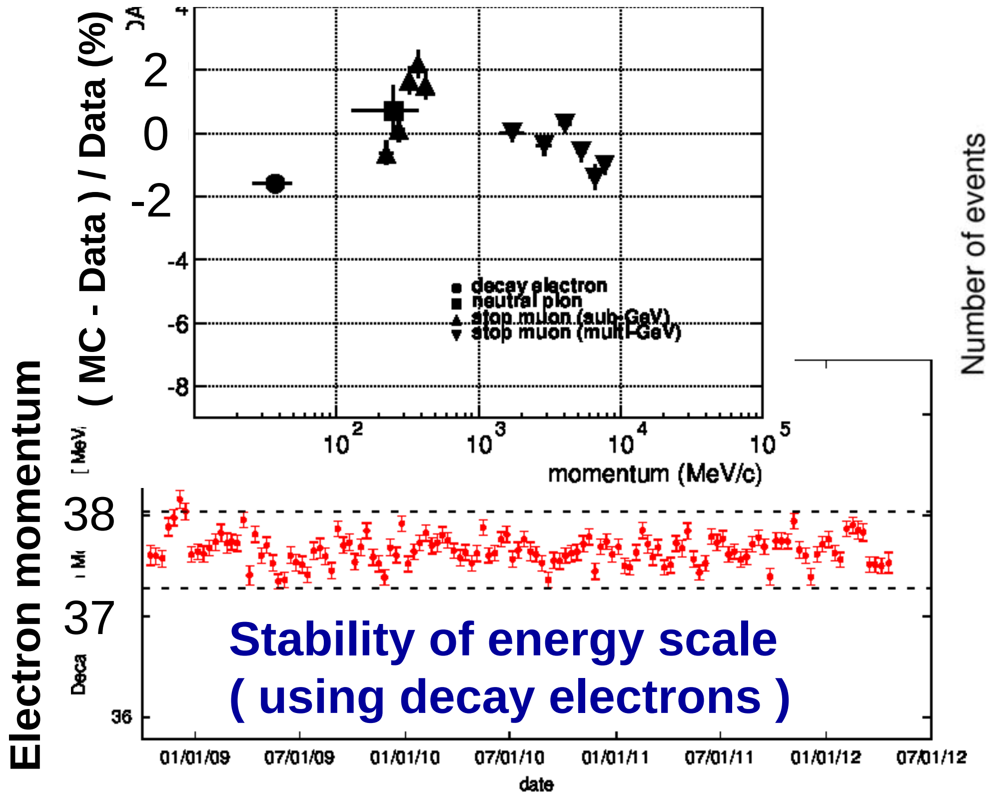
Contributions from SK (ICRR)

4) Provide relevant calibration / reference data

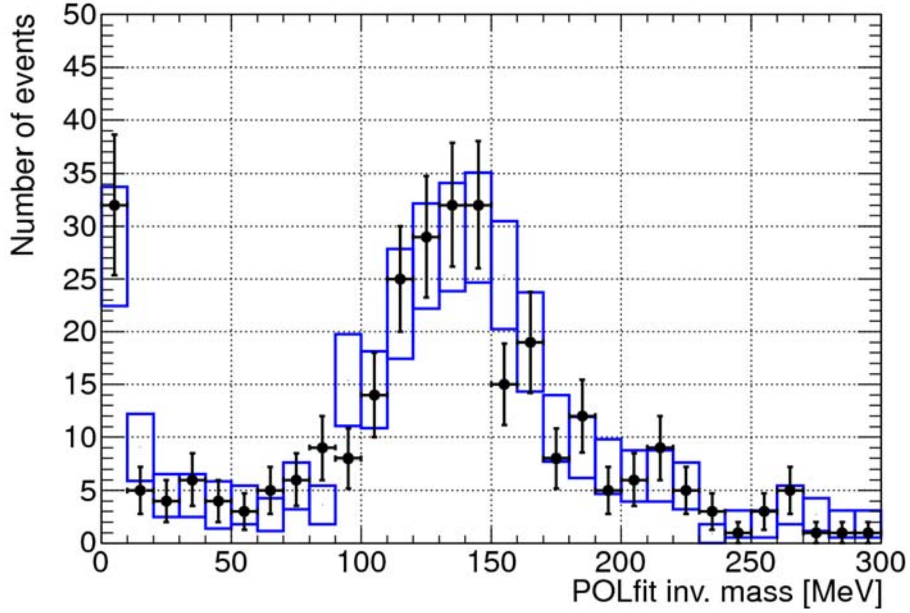
5) Provide neutrino interaction simulation library / programs,
detector simulation programs
and also SK simulation data for T2K.

6) Evaluate / provide systematic uncertainties in SK

Uncertainty in the energy reconstruction

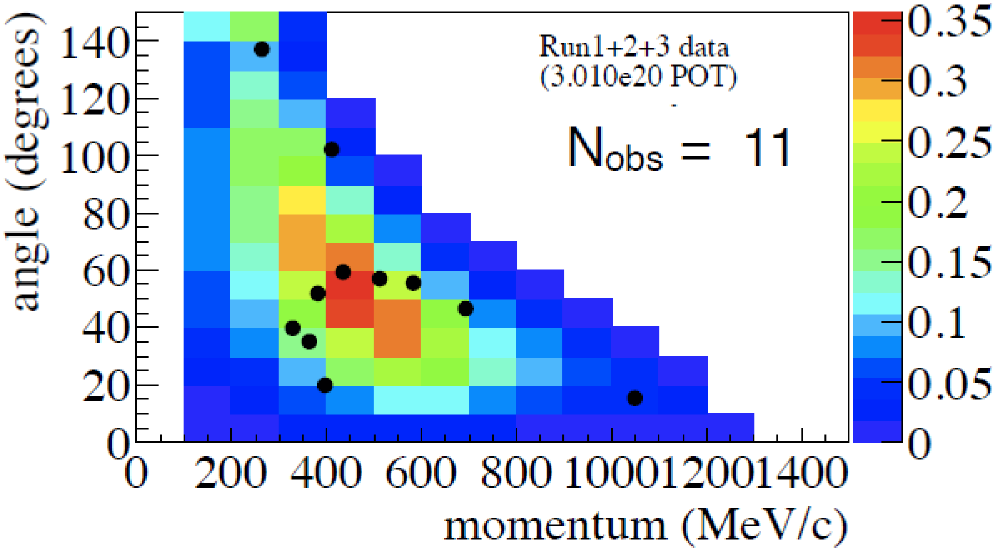


Reconstructed π^0 mass from the special π^0 fitter



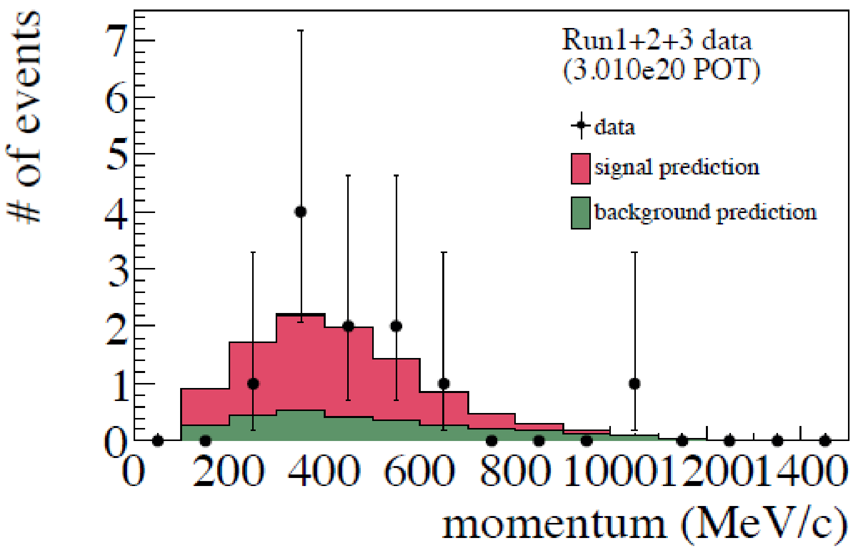
Oscillation analysis ~ ν_e appearance ~ θ_{13}

Search for ν_e candidates

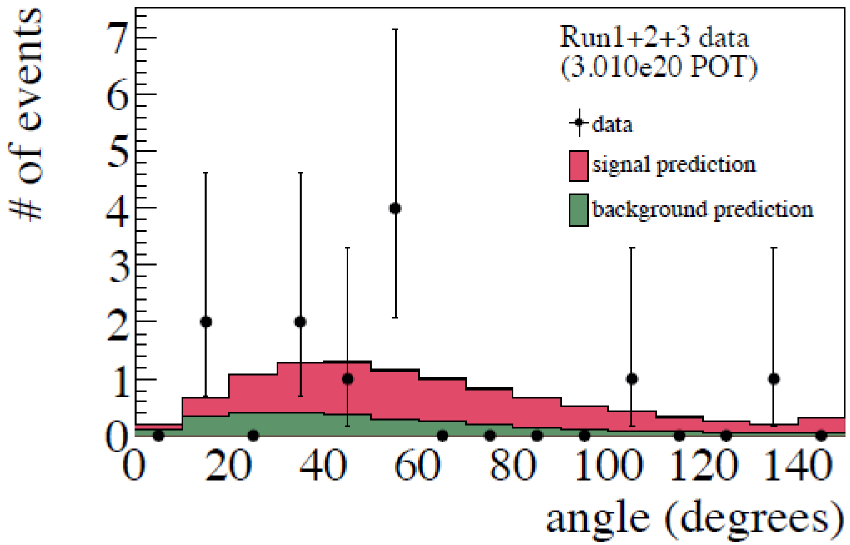


Use $\nu_e\, p \rightarrow e^-\, n$
(CC quasi-elastic) events

1 ring e-like events
+ no decay electrons
(reject invisible μ, $\pi^{\pm}$)
+ additional π^0 rejection



(prediction histograms are based with best-fit $\sin^2 2\theta_{13}$)



Oscillation analysis ~ ν_e appearance ~ θ_{13}

Search for ν_e candidates

The predicted # of events w/ 3.01 x 10^{20} p.o.t.

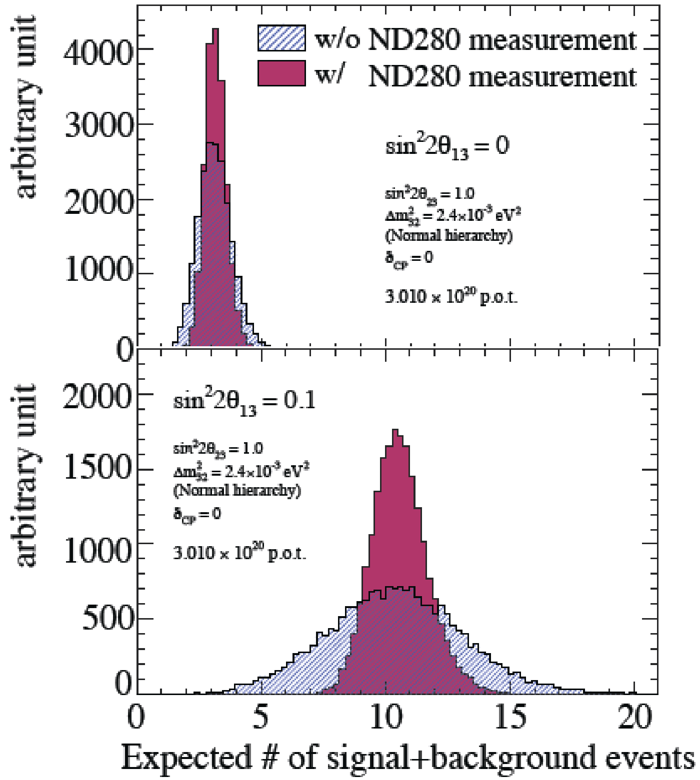
Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ⁰)	1.21	1.21
$\overline{\nu}_\mu + \overline{\nu}_e$ background	0.16	0.16

Systematic uncertainties

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

big improvement from the T2K 2011 results

the predicted # of event distribution



Uncertainties are reduced using ND280 measurement

Oscillation analysis ~ ν_e appearance ~ θ_{13}

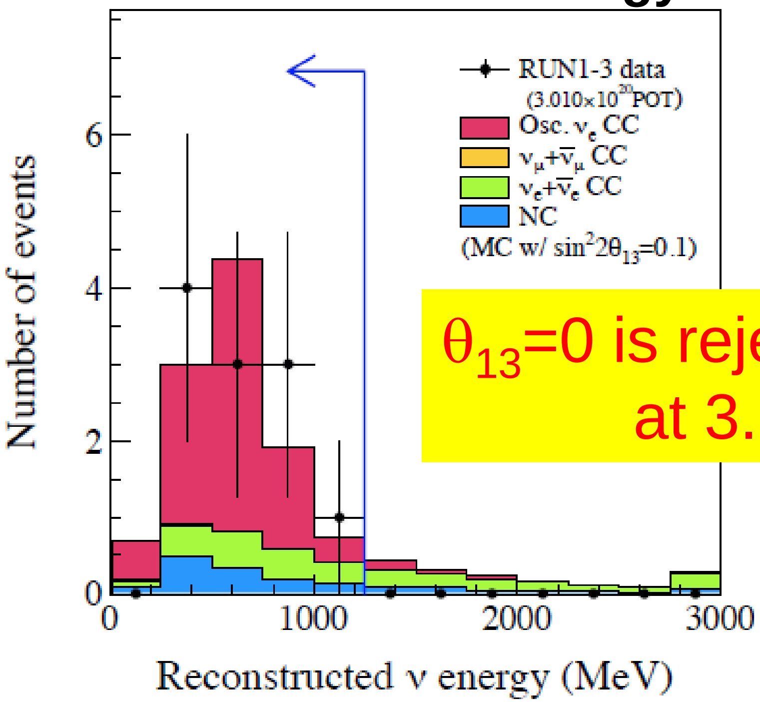
Search for ν_e candidates

Observed 11 events

Expected # of background

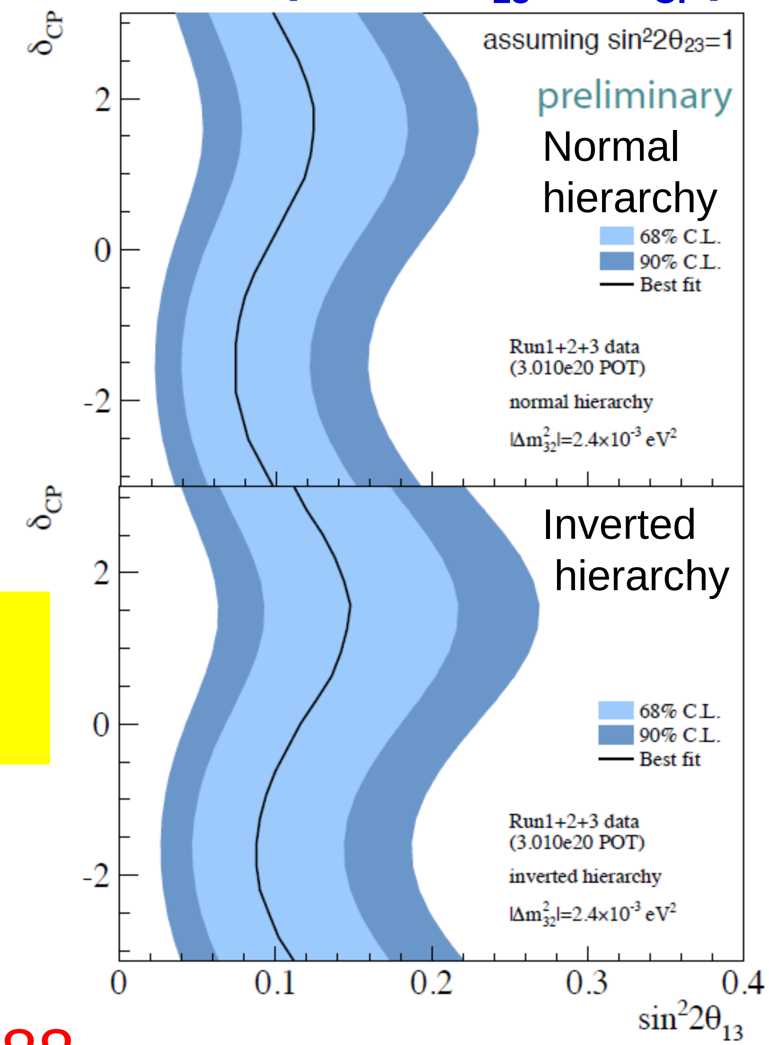
3.2 ± 0.43 (syst.) for $\sin^2(2\theta_{13})=0$

Reconstructed ν energy



$\theta_{13}=0$ is rejected at 3.2σ

Allowed regions ($\sin^2 2\theta_{13}$ & δ_{CP})

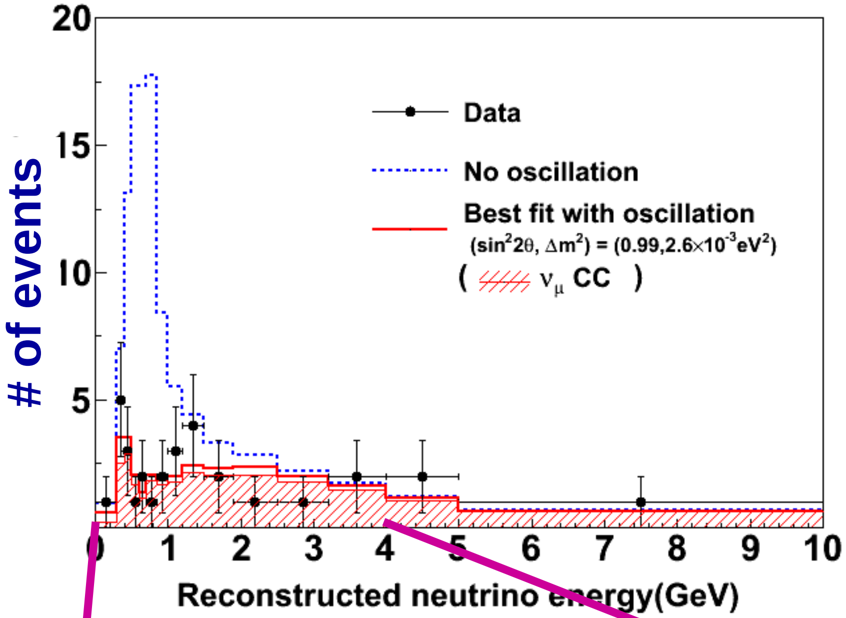


$0.033 < \sin^2 2\theta_{13} < 0.188$

Best fit : $\sin^2 2\theta_{13} = 0.11$

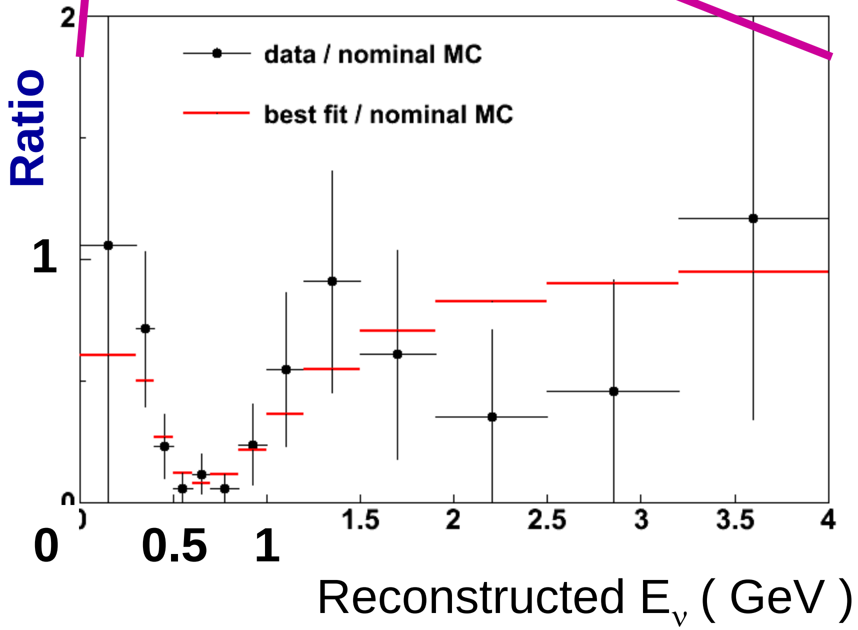
(for $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\delta_{CP}=0$)

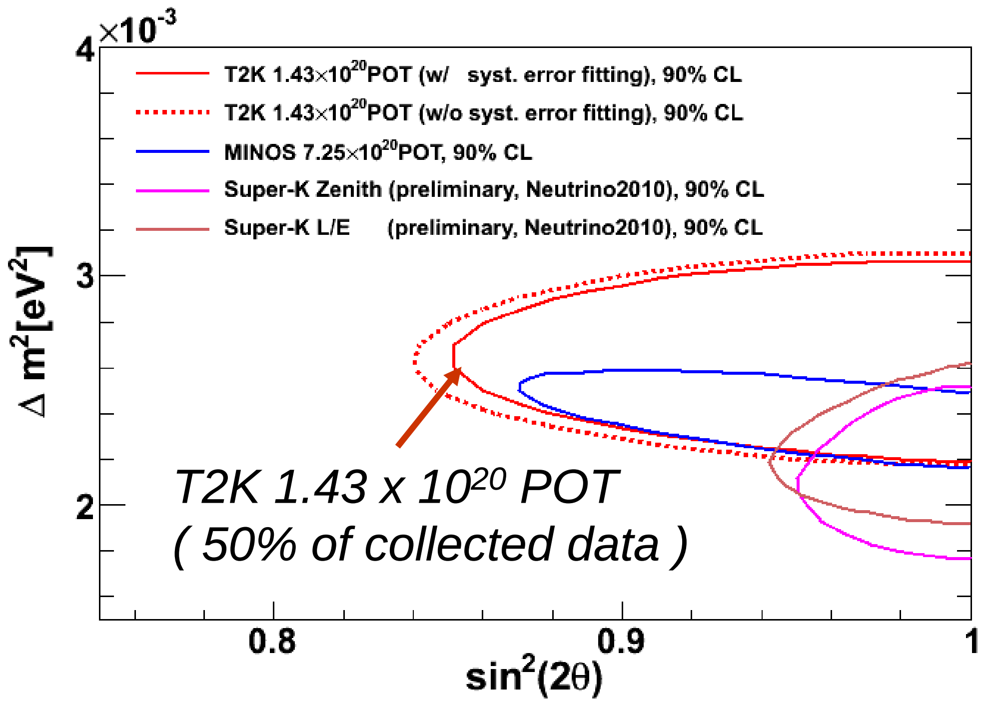
Oscillation analysis ~ ν_μ disappearance ~ Δm^2_{23} & θ_{23}



Use 1 ring μ-like events
~ Dominated by CCQE ~

→ Reconstruct energy of neutrino
using observed μ direction
and momentum
together with ν direction.





Summary

T2K has been collecting data since Jan. 2010.

J-PARC facilities including neutrino facility
were damaged by the earthquake.

But recovered in an year and started its operation in 2012.

Now, accelerator was recovered in an year
and we have resumed the experiment.

Beam power is now at 210kW.
(Before the earthquake, maximum power was ~ 150kW)

Super-Kamiokande is providing verified high quality data
with high efficiency (live time ratio > 99 %).

Also, we provide essential simulation programs
(neutrino interaction simulation library and
SK detector simulation program)
and reconstruction tools.

Systematic errors related to SK is also provided
to be used in the analyses.

Summary

In 2011, we have reported
the 1st indication of the non-zero θ_{13}
(Observed ν_e appearance signal)

→ With the data taken in 2012 (3.0×10^{20} POT),

Observed # of events : 11
expected background : 3.2 ± 0.43 (syst.)
for $\sin^2(2\theta_{13})=0$

non-zero θ_{13} is rejected at 3.2 σ level.

$0.033 < \sin^2 2\theta_{13} < 0.188$ @ 90% C.L.

(for $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\delta_{CP}=0$)

We have also reported the allowed region of Δm^2_{23} and θ_{23}
(ν_μ disappearance analysis)
and it was consistent with the past experiments.

fin.