Results from the first year of running of T2K

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(IPNS, KEK / J-PARC)
for
T2K collaboration

T2K Collaboration

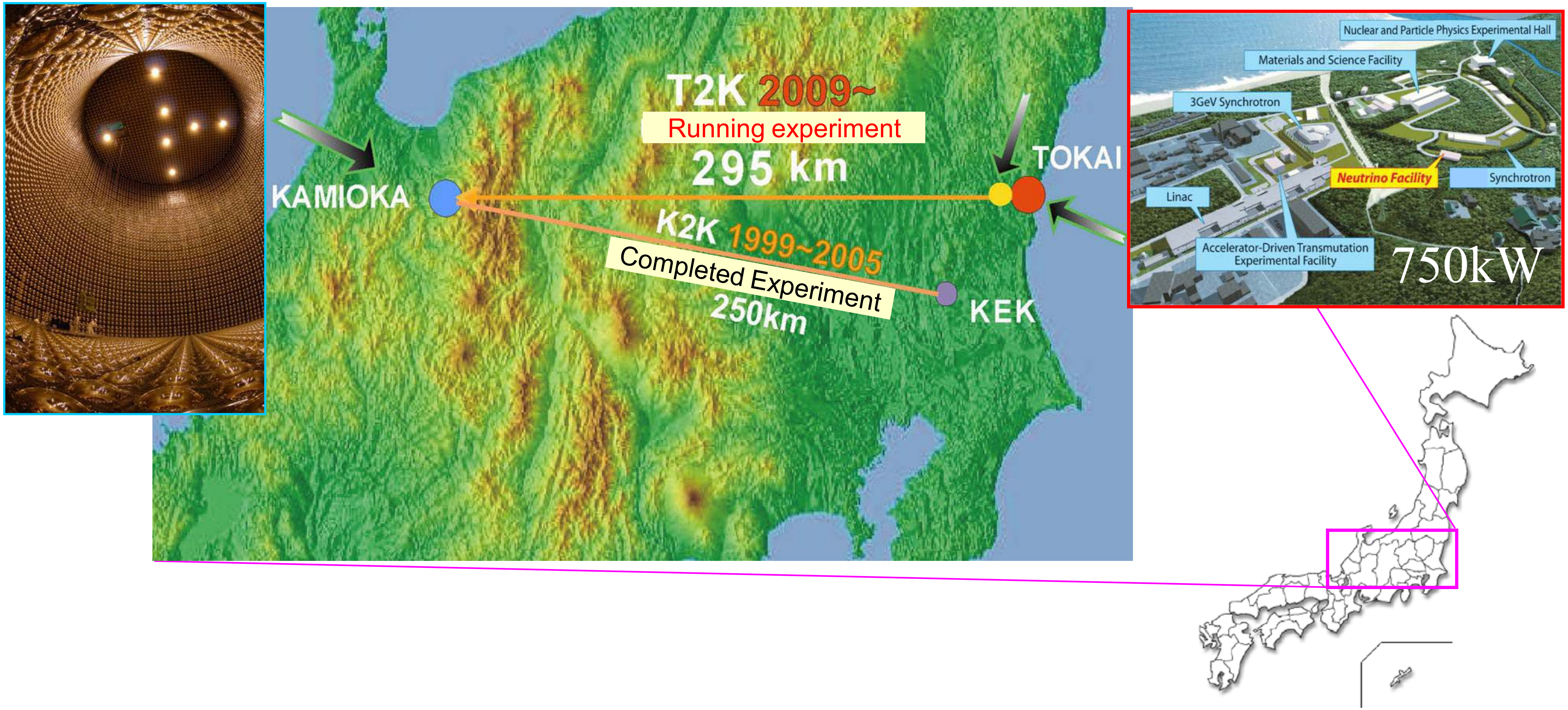
- 12 Countries
  - Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, USA
- 59 Institutions, ~500 members.

Contents

- Introduction: ν physics which T2K explores.
- Principal of T2K experiment
- Experimental setup of T2K
  - Generating ν beam $\rightarrow$ Observing at SK.
- Data taking status
- Oscillation analysis for 1st data-set
  - Analysis method
  - Systematic uncertainties
  - *T2K oscillated ν_e appearance candidate?*
- Next milestone

Introduction

T2K (Tokai to Kamioka) LBL ν experiment



- Searches for $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)
- Precise measurement of $\nu_\mu \rightarrow \nu_\mu$ (ν_μ disappearance)

Main Physics Goal

- Searches for $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)

Flavor eigenstate

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

Mass eigenstate

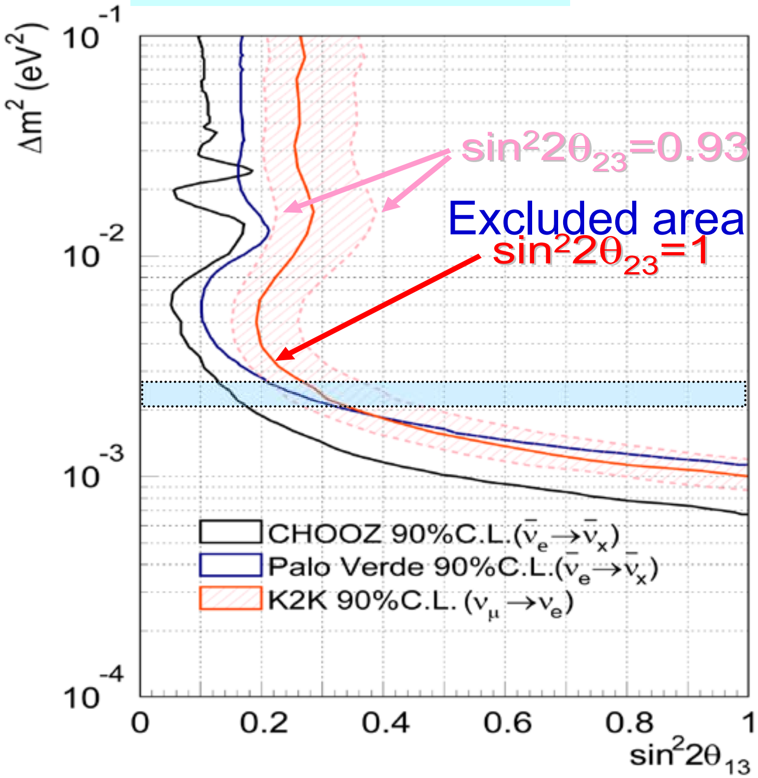
$\theta_{23} \sim 45°$
$\Delta m^2_{23} \sim 2.5 \times 10^{-3}$ [eV^2]

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

$\theta_{13} << \theta_{12}, \theta_{23}$

θ_{13}, δ are still unknown.

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\Delta m^2_{31} L/4E\right)$$
$$\mp 4J_r \sin\delta \sin\left(\Delta m^2_{21} L/2E\right) \sin^2\left(\Delta m^2_{31} L/4E\right) + \ldots$$



- θ_{13} can be determined from $\nu_\mu \rightarrow \nu_e$.

Main Physics Goal

- P ($\nu_\mu \rightarrow \nu_e$) includes the CP violation term

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\Delta m^2{}_{31} L/4E\right)$$
$$\mp 4 J_r \sin\delta \sin\left(\Delta m^2{}_{21} L/2E\right) \sin^2\left(\Delta m^2{}_{31} L/4E\right) + \ldots$$

– for ν
+ for $\bar{\nu}$

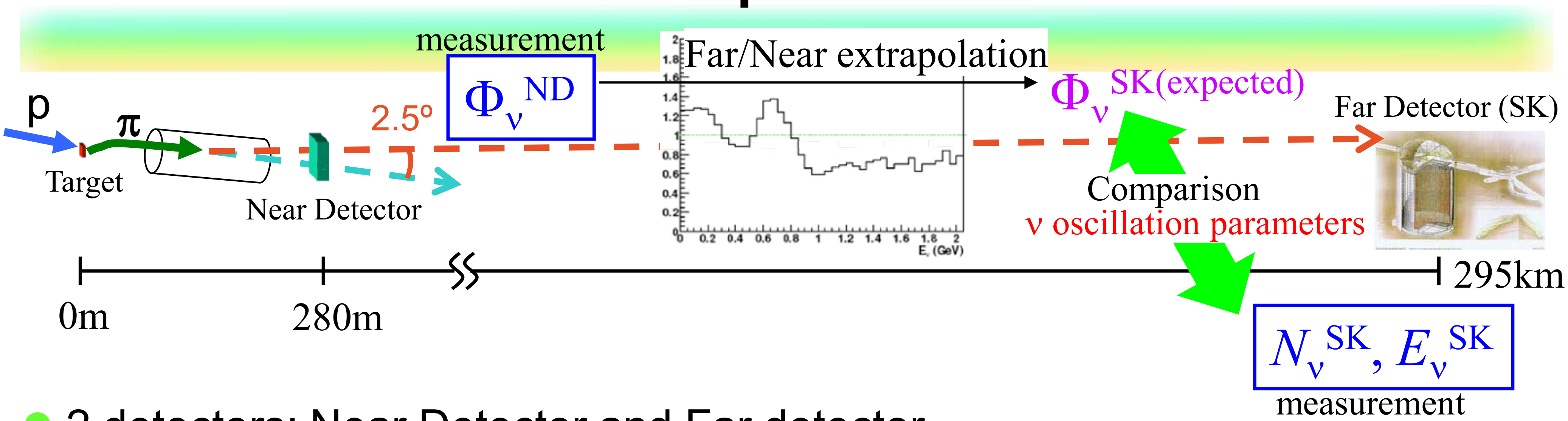
(Approximation @ $\Delta m^2{}_{31} L/4E \sim \pi/2$, $\Delta m^2{}_{32} \sim \Delta m^2{}_{31}$)

$$J_r \equiv \cos\theta_{12} \sin\theta_{12} \cos\theta_{23} \sin\theta_{23} \cos^2\theta_{13} \sin\theta_{13}$$

- If P ($\nu_\mu \rightarrow \nu_e$) is measureable size, it can be a probe to search the CP violation in lepton sector in future experiments.

Experimental setup of T2K

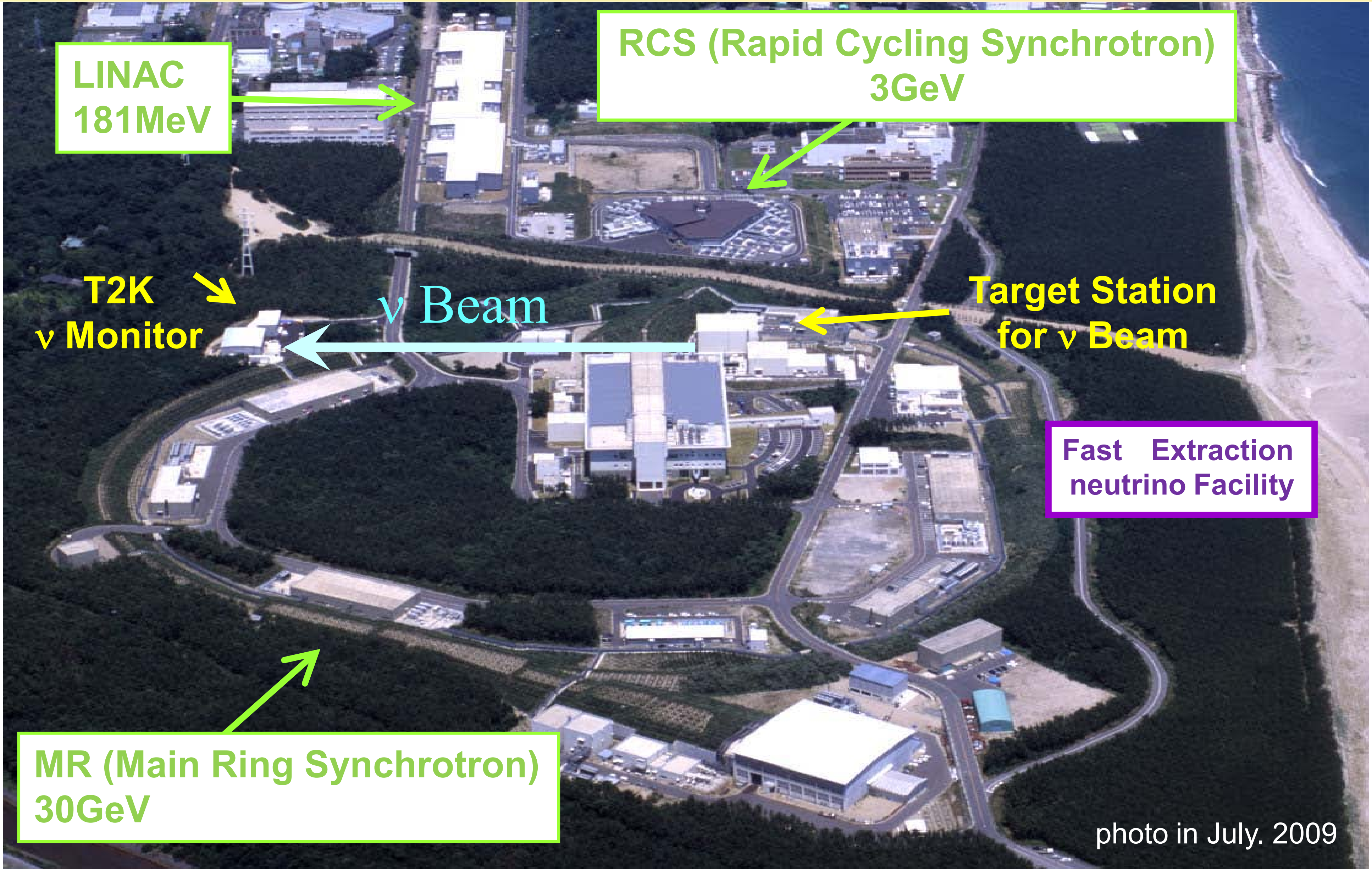
Concept of T2K



- 2 detectors: Near Detector and Far detector
  - Generate the high intensity ν_μ beam
  - Measure the neutrino flux by Near Detector : $N_\nu^{ND} = \times\ \Phi^{ND}(\nu_\mu) \times \sigma(\nu\ \text{interaction}) \times \varepsilon^{ND}$
  - Extrapolate the flux to Far detector position: $\Phi^{SK}(\nu_\mu) = R(SK/ND) \times \Phi^{ND}(\nu_\mu)$
  - Calculate the expected the number of event as a function of oscillation probability:

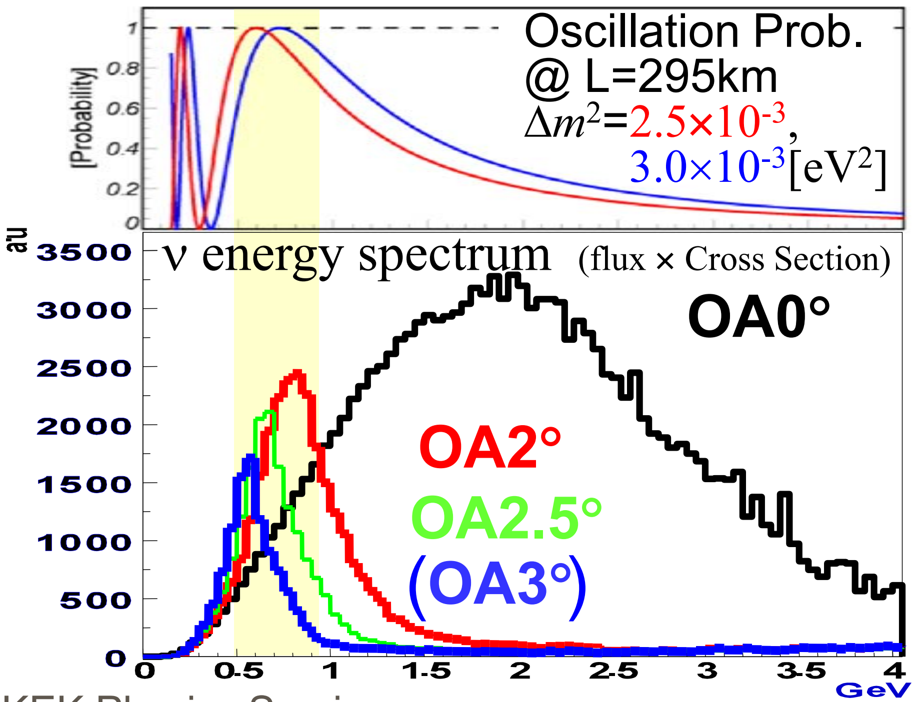
    $N\nu e^{SK\ (expected)} = P(\nu_\mu \rightarrow \nu_e) \times \Phi^{SK}(\nu_\mu) \times \sigma(\nu\ \text{interaction}) \times \varepsilon^{ND}$
  - Determine oscillation probability by comparing the expected # of events and # of observed events.

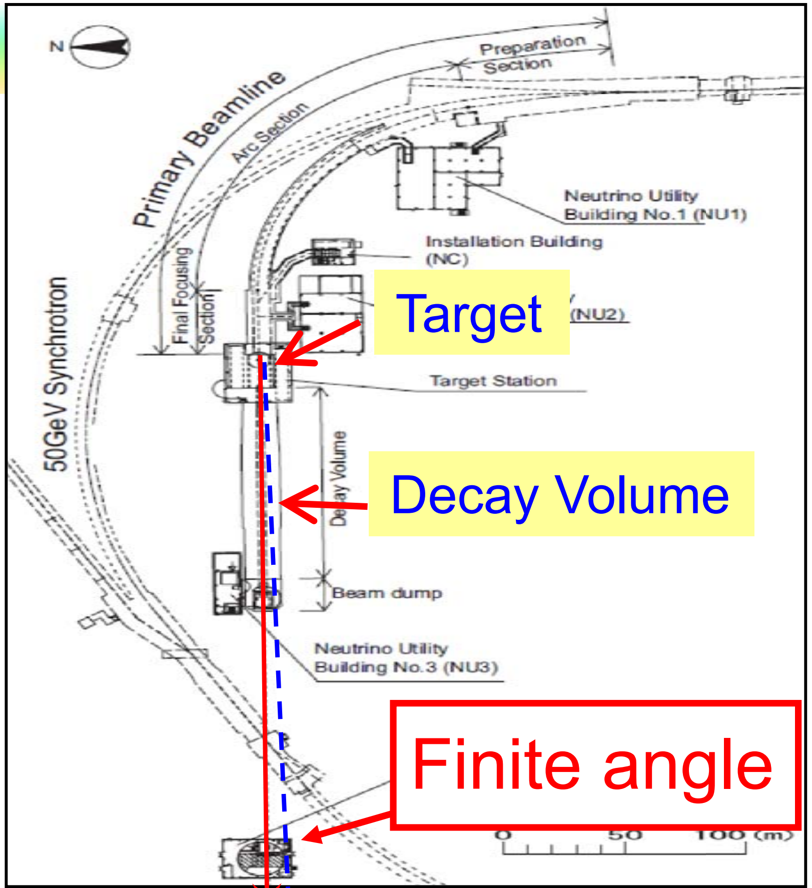
J-PARC : Accelerator

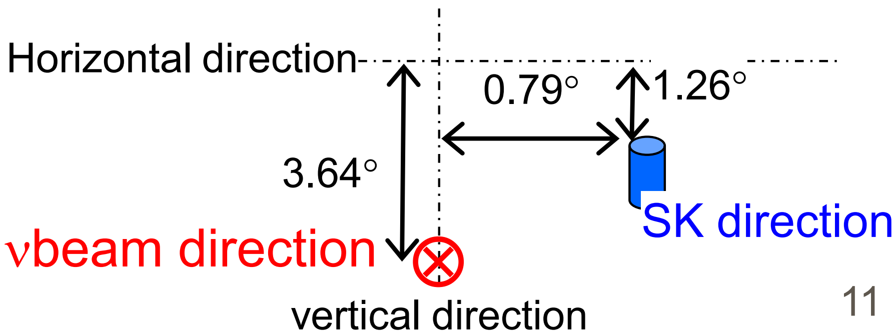


Off axis beam

- Pseudo-Monochromatic beam by Off-Axis method (ref. BNL E899)
  - $\nu\mu$ beam direction is different from Far detector direction.
  - Current Off axis angle is <u>2.504°</u>
- Set peak of (flux × σ_{CC}) @ oscillation max.
  - Minimize the high energy neutrino flux to reduce the background events.





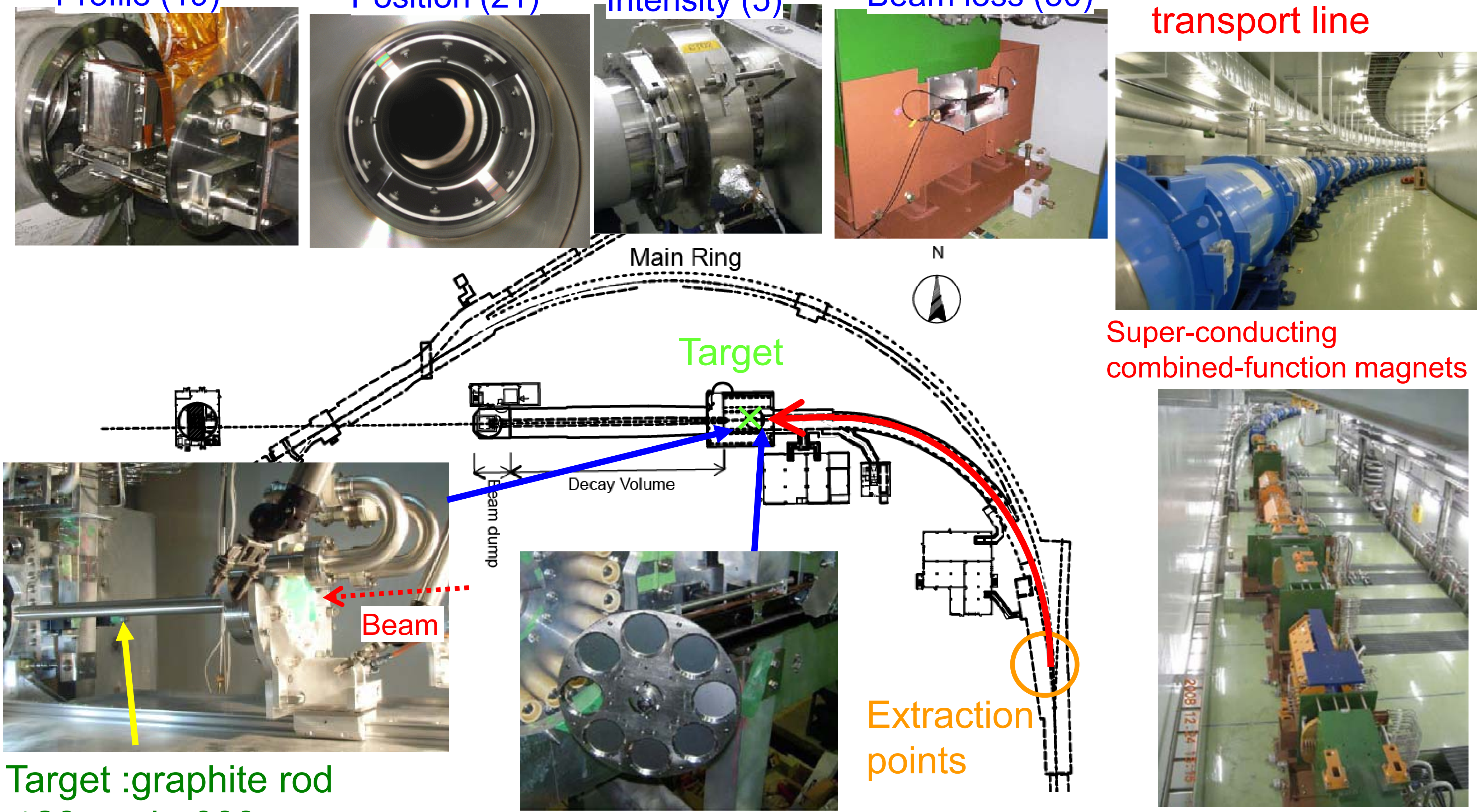


J-PARC ν beam line :Primary-line

Beam monitors are install along the proton beam transport

Profile (19) Position (21) Intensity (5) Beam loss (50)

Primary proton transport line

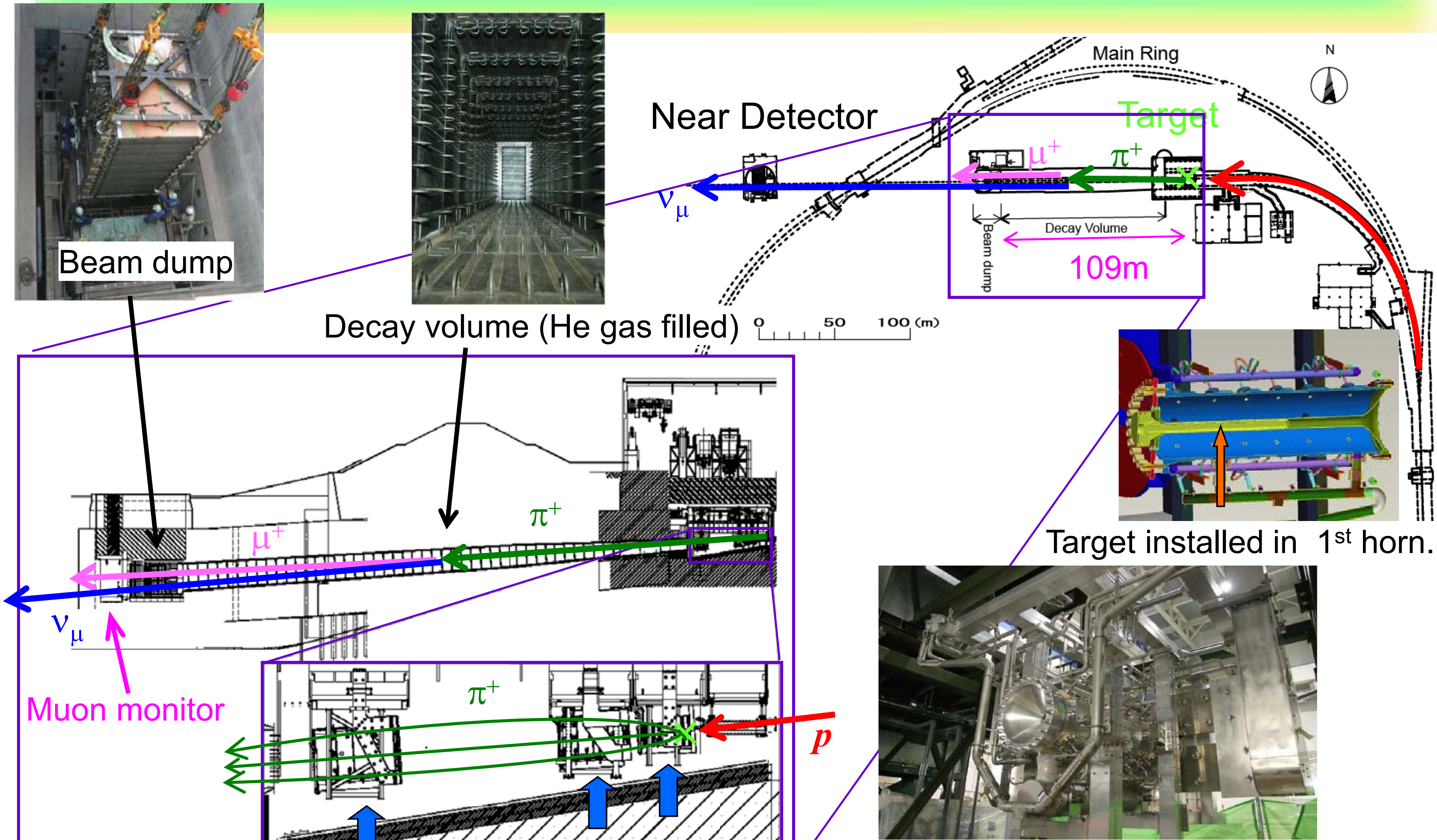


Target :graphite rod
ϕ26mm,L=900mm

Optical Transition Radiation (OTR) Profile monitor

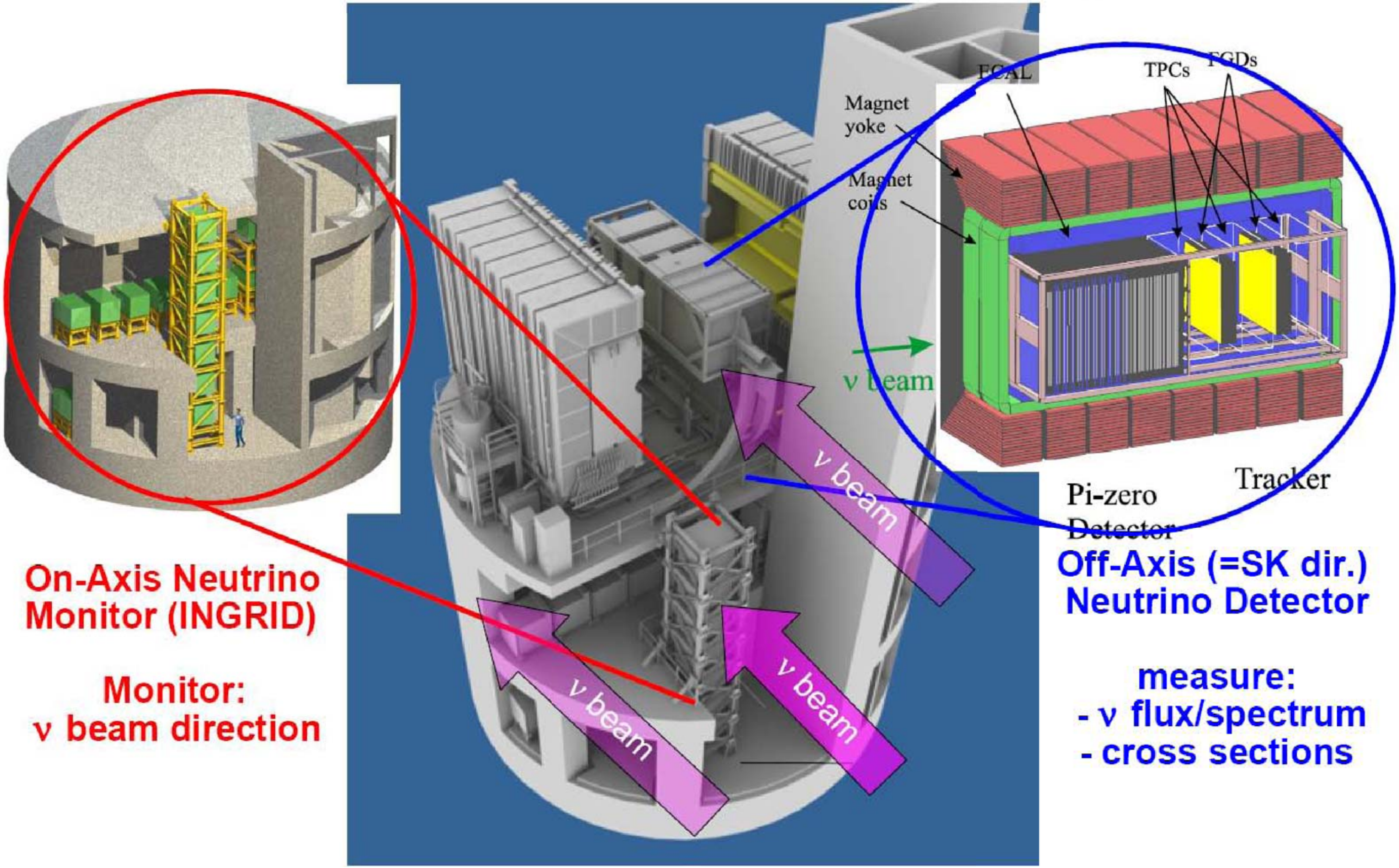
Normal-conducting magnets

J-PARC ν beam line: secondary line



Pions are focused by
3 electromagnetic Horns.

Near Detectors



On-Axis Neutrino Monitor (INGRID)

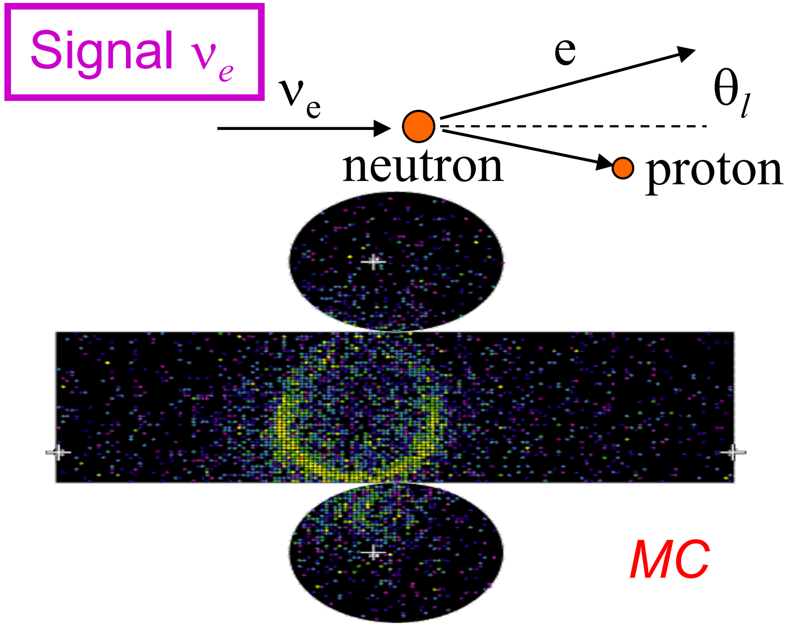
Monitor:
ν beam direction

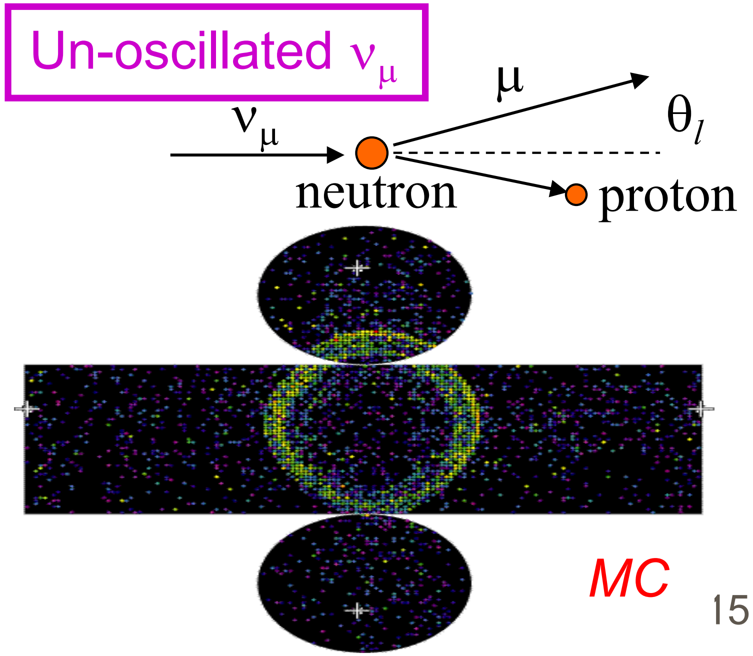
Off-Axis (=SK dir.) Neutrino Detector

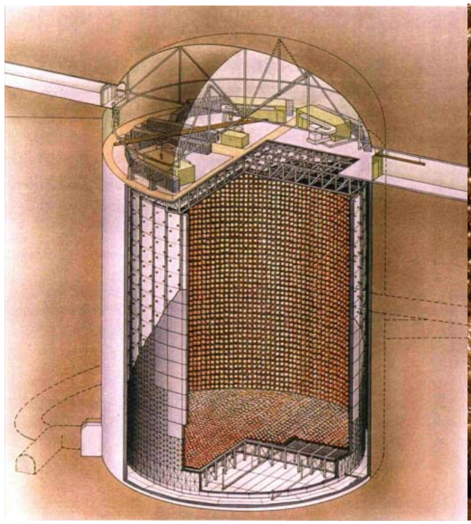
measure:
- ν flux/spectrum
- cross sections

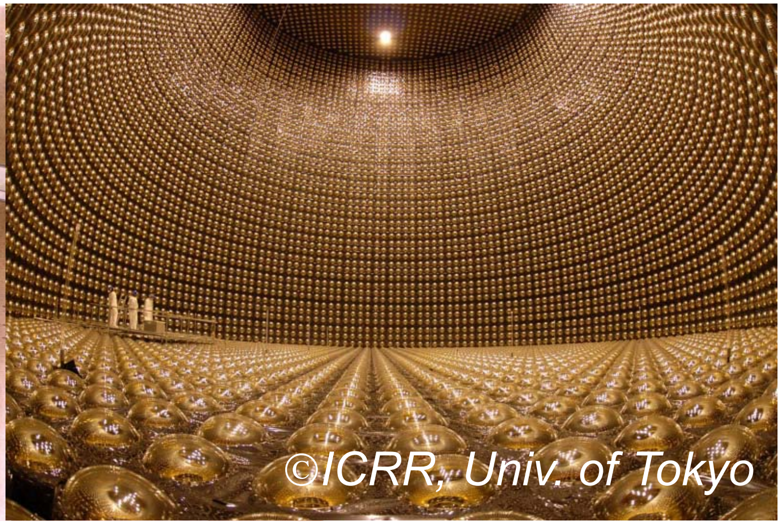
Far Detector: SK-IV

- 50kt Water Cherenkov detector (Fiducial 22.5kt) @ underground (2700 m water equivalent)
- 20' ID PMT×11,129: 40% Photo coverage + 8' OD PMT×1885 :
- Dead-time less DAQ system (2008~)
- Good performance for sub-GeV ν detection
  - 1st oscillation maximum : $E\nu$ ~0.6GeV at SK position.
  - Charged current quasi-elastic (CC QE) interaction is dominant process.
    - Good e / μ separation
    - Energy reconstruction: $\Delta E/E$ ~10% (←2-body kinematics)



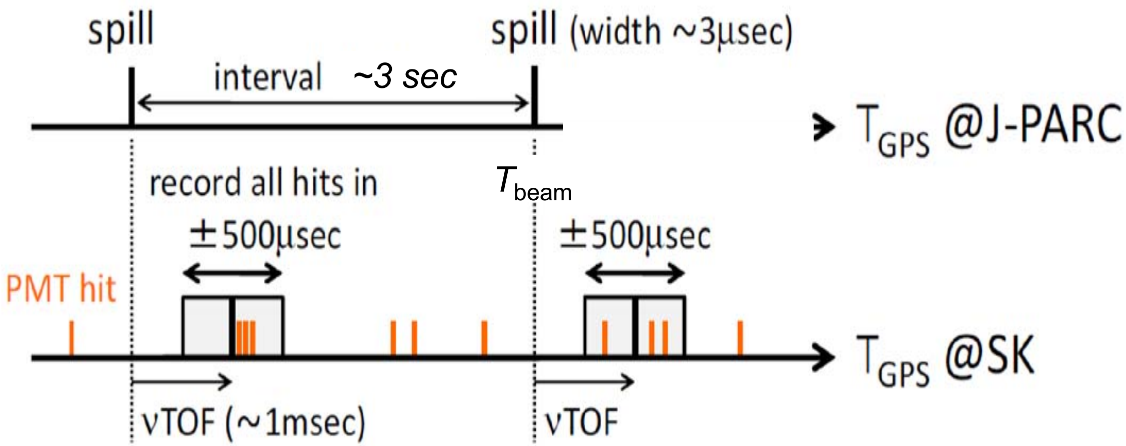


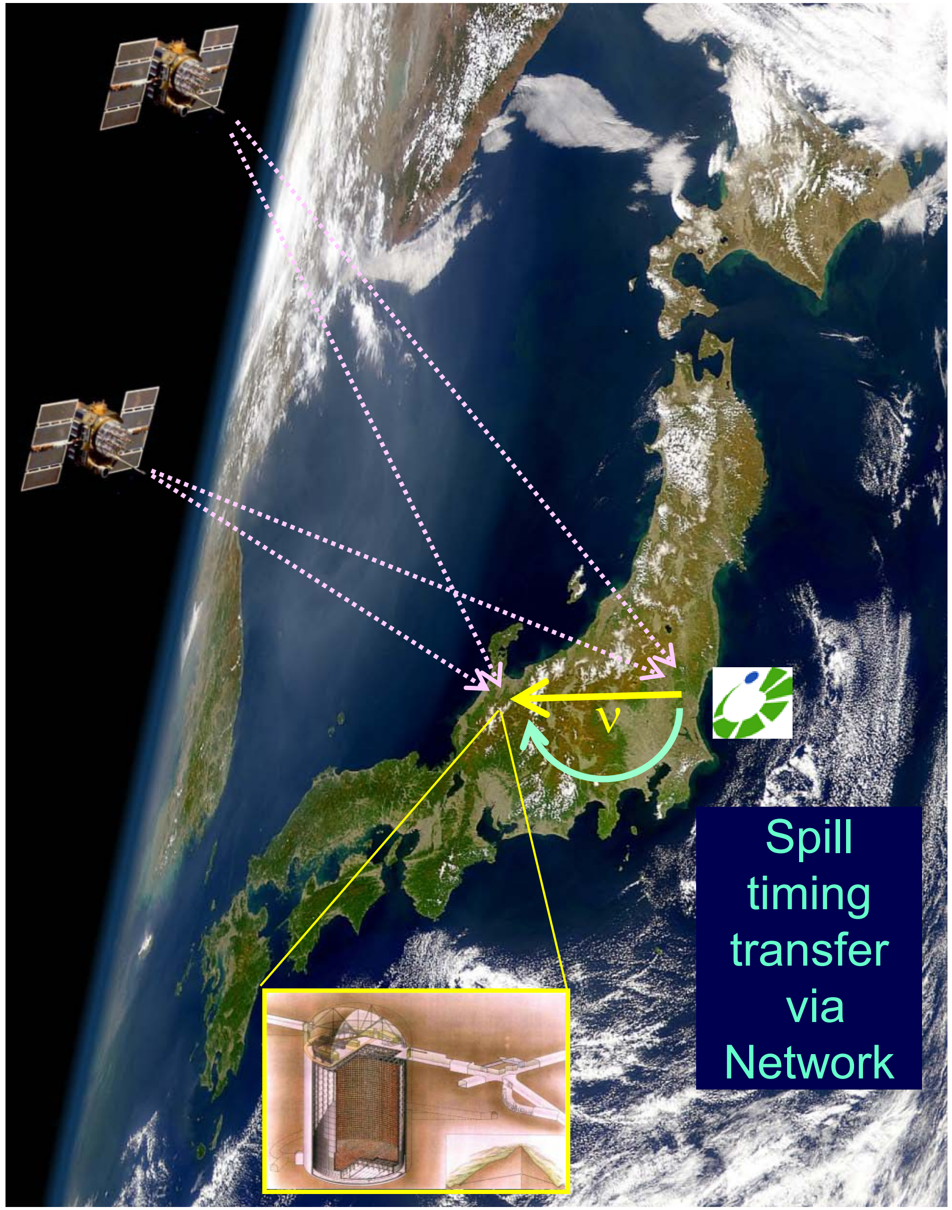




GPS: Event synchronization

- **Baseline measurement (Survey)**
  - L = 295,335 ± 0.7 m
    → ToF of ν = 985.132 ± 0.002 μsec (≡ νTOF)
  - Expected event timing @ SK (≡T_{SK})
    = Spill timing @ Tokai (≡T_{beam}) + νTOF.
- **DAQ synchronization**
  - SK signals in ±500μs timing window are recorded as "T2K beam events".
  - Stability of GPS is checked by comparing 2 GPS hardware and atomic clock.
    → Require |GPS1-GPS2| < 200nsec

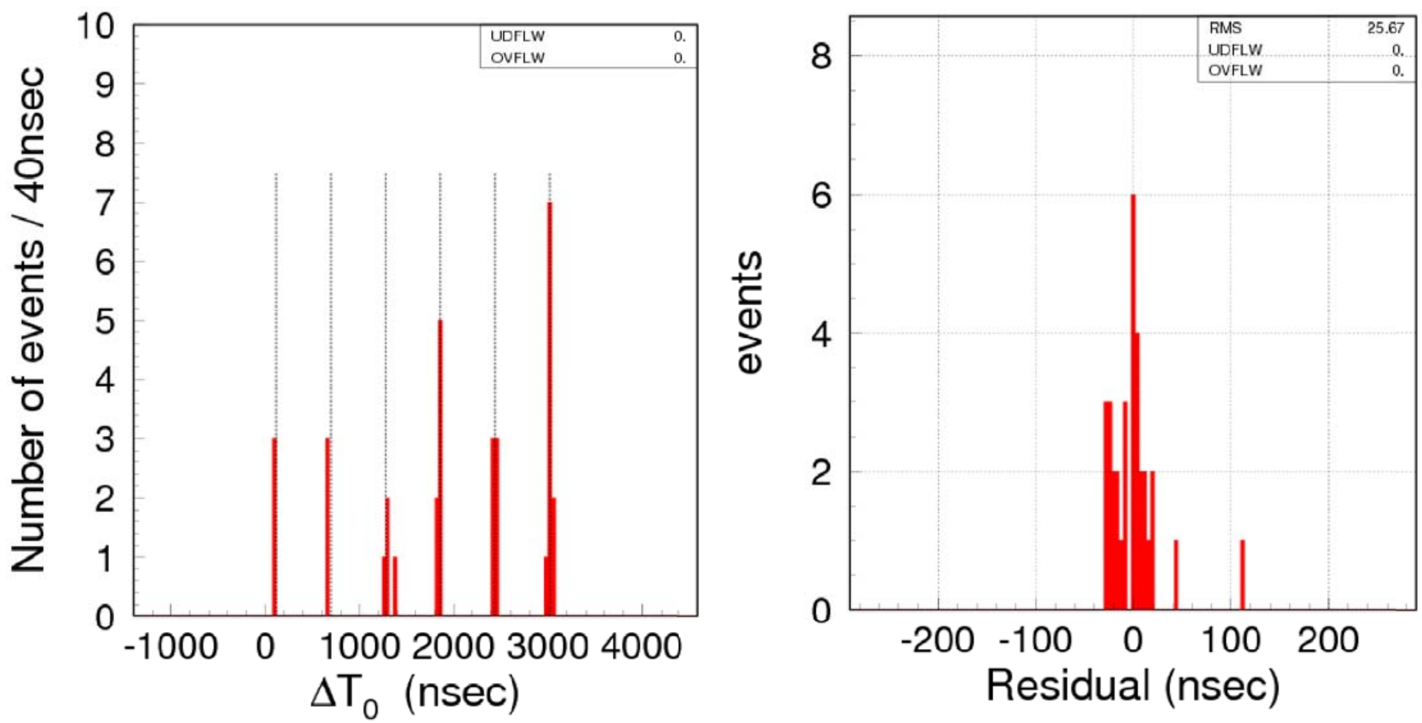




Event timing @ Far detector

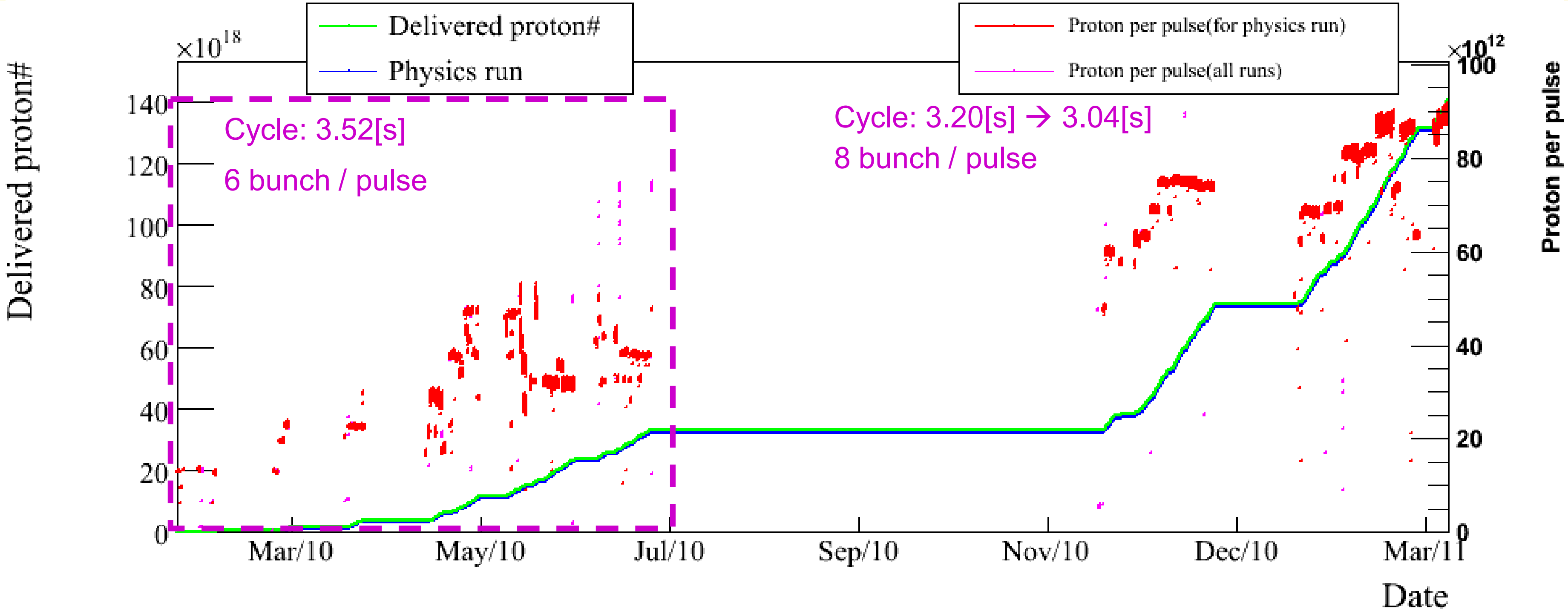
- Candidate of Fully contained events is localized in ±100ns from the corresponding bunch timing.
  - Fully contained events … Neutrino interact with water in the inner detector and all produced particles stop in the inner detector. (No Outer detector signal)

2010 Jan~Jun(6 bunch beam)



Running status of T2K

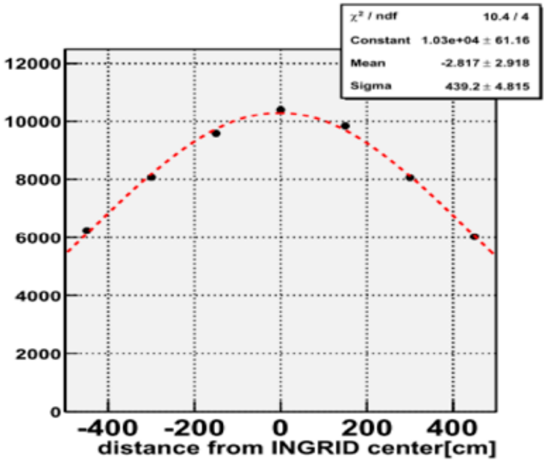
Accumulated # of protons so far

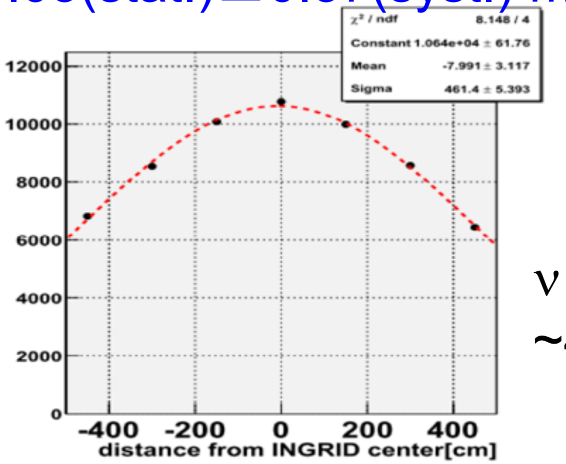


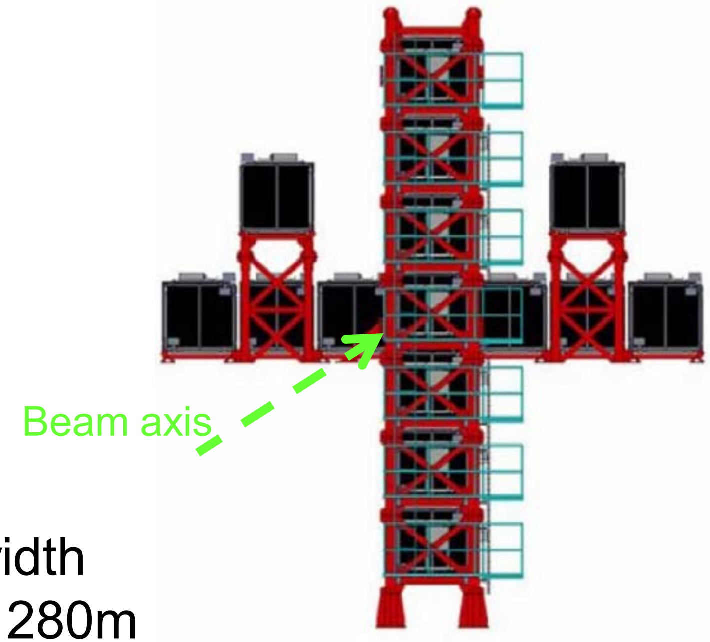
- T2K physics run: 2010, Jan~
  → Now: ~9.3×10^{13}[p/pulse], 3.04[s] cycle
  → Beam power = 145kW
  Integrated POT reaches 1.45×10^{20}.
- Physics results shown in this report
  - Analysis of the data taken from Jan. 2010 to Jun. 2010.

Quality of neutrino beam

- Targeting efficiency of proton beam ~99%.
- ν Beam direction measured by INGRID from 2010 Jan. ~ Jun.
  - Horizontal: +0.01±0.05(stat.)±0.33(syst.) mrad
  - Vertical : -0.24±0.05(stat.)±0.37(syst.) mrad

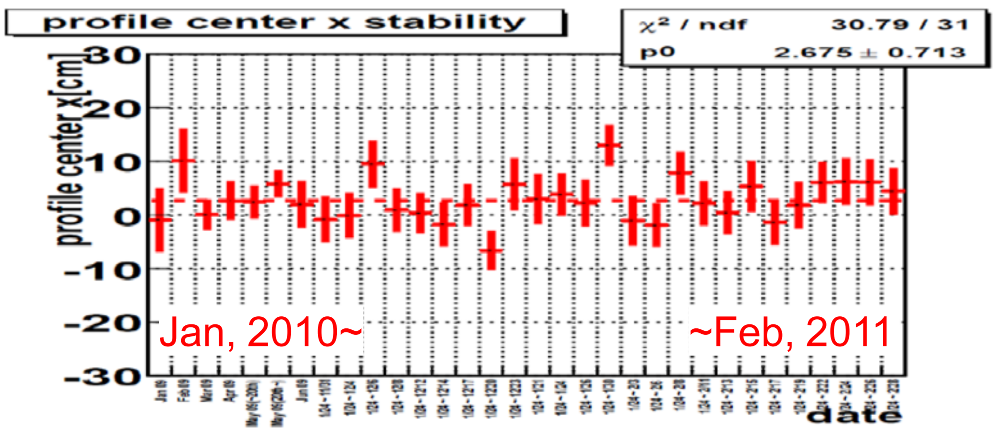


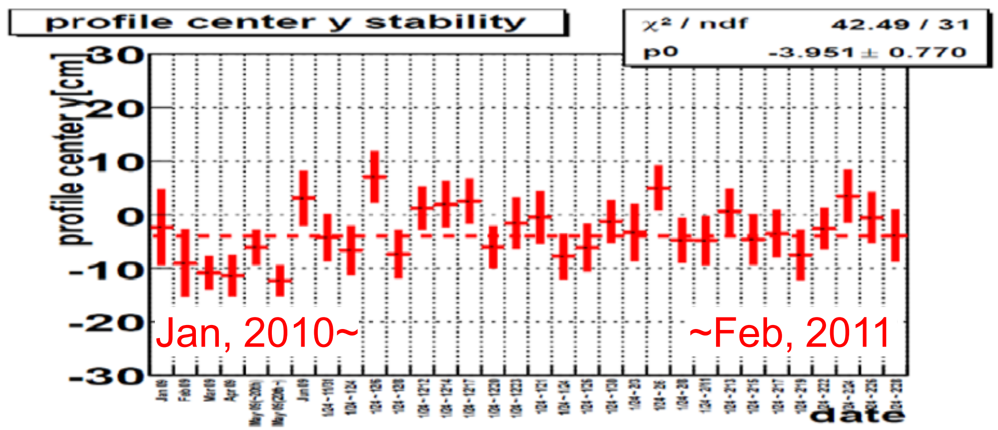




ν beam width
~4.5m @ 280m

Stability: Vertical





Oscillation analysis for 1st data set

Outline of analysis ν_e appearance search

1. Calculate expected # of event as a function of oscillation parameters: θ_{13}, Δm^2_{13}
   - $N_{SK}^{MC} = \int dE\, \Phi_{SK}(E) \times \sigma_{SK}(E) \times \varepsilon_{SK}(E) \times P(\nu_\mu \to \nu_e; E; \theta_{13}, \Delta m^2_{13})$
     - N_{bkg}^{MC} also should be estimated.
   - ND280 $\rightarrow$ $R_{DATA/MC} \equiv N_{ND}^{DATA} / N_{ND}^{MC}$

   $\rightarrow N_{SK}^{expected} = R_{DATA/MC} \times (N_{SK}^{MC} + N_{bkg}^{MC})$
2. Select events ν_e candidate from data.
   - Select the “good beam spill”
   - T2K event selection
     - Select Fully Contained events in Fiducial Volume
     - Ring counting → Select CC-QE candidate
     - PID : separate ν_e from ν_μ events
     - Background rejection cut $\rightarrow N_{SK}^{obs}$
3. Estimate the oscillation parameter from $N_{SK}^{expected}$ and N_{SK}^{obs}.

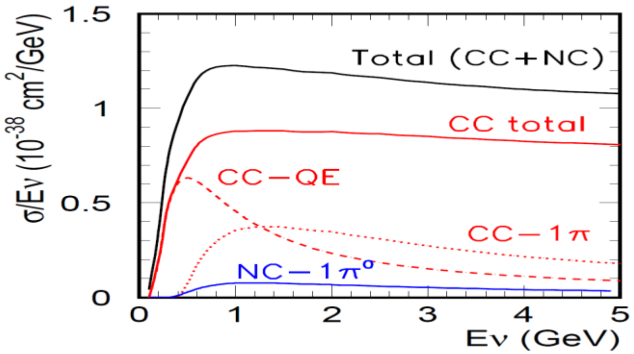
1. Estimation of Expected # of event

Background events for T2K

- Background for ν_e appearance search.
  - π^0 from NC events
  - Intrinsic ν_e contaminated in ν_μ beam

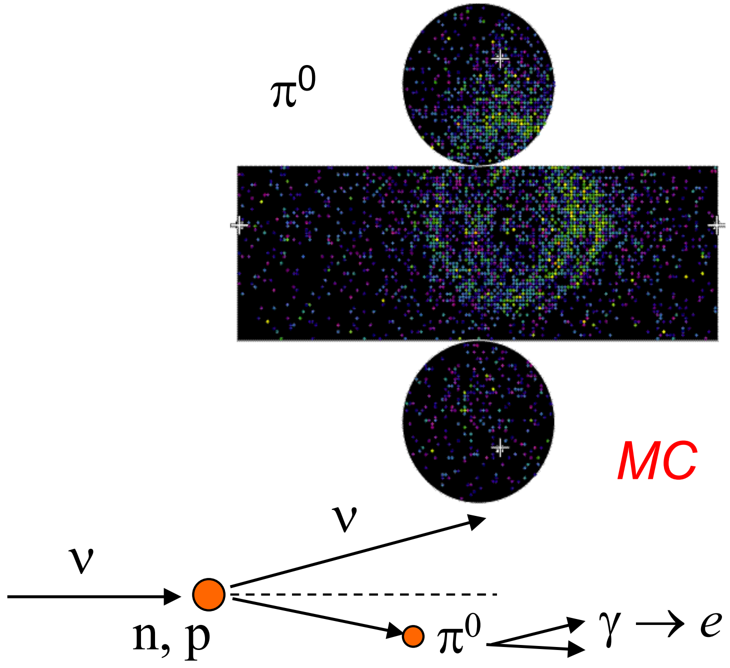
    ← Dominant sources are μ^+ decay and K^+ decay
    - ✓ Estimate from π, K production at target.
    - ✓ Measure the flux by Near Detector.
- Background for ν_μ disappearance
  - CC non-QE events w/ missing particle

    … Eν reconstruction is not correct.
- Interaction cross section for background events become large as the neutrino energy become large.

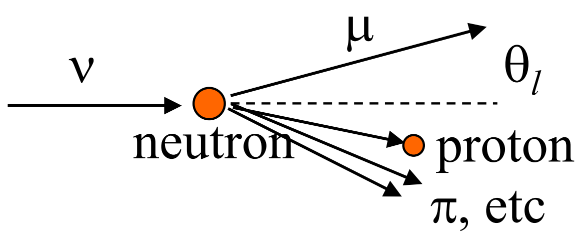


→ Reduced high energy ν flux is important to keep S/N ratio enough high.

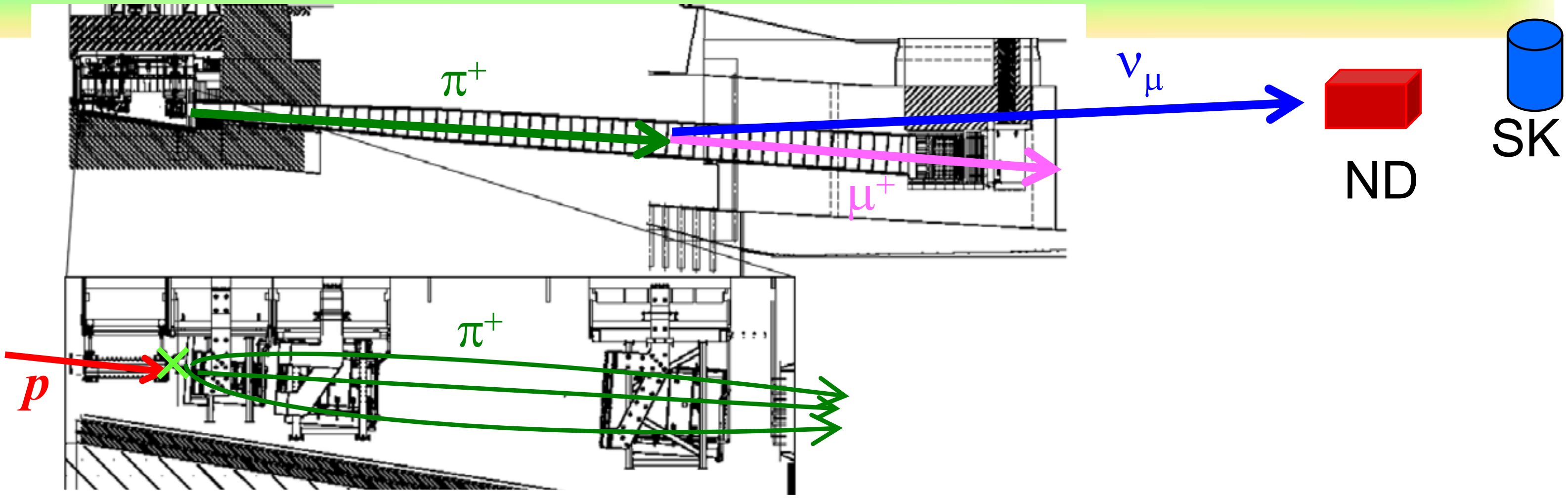
NC π^0 production



CC non-QE interaction



T2K: Flux prediction (Beam MC)



(1) Hadron production by p+C interaction and secondary interaction in target is simulated using FULKA framework.

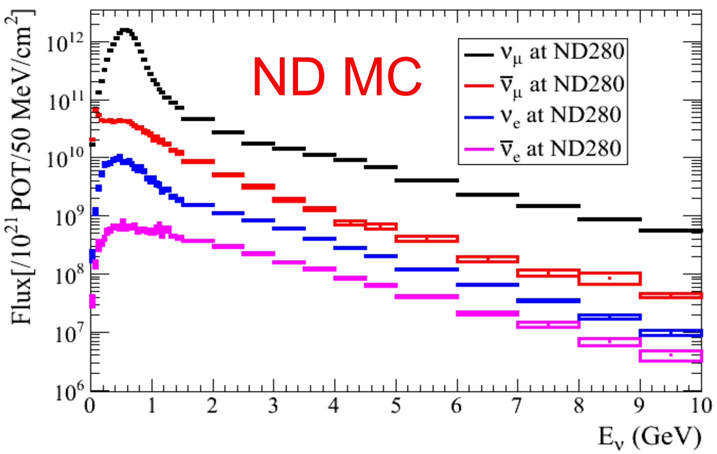
* Pion production cross section is corrected using NA61 data → next page.

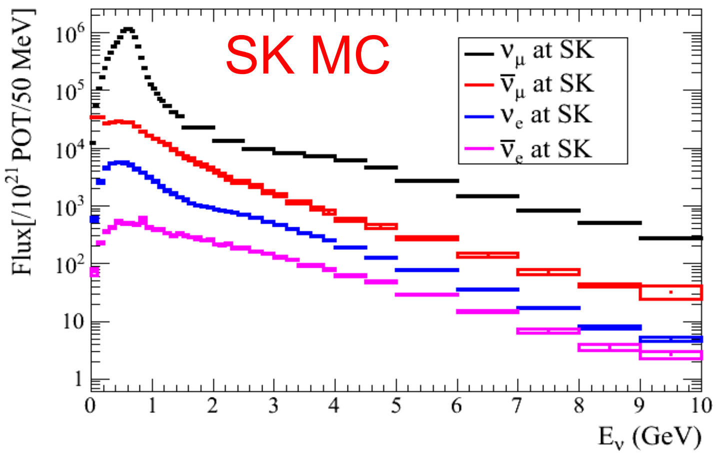
* Measured proton parameters is assumed.

(2) Propagation of produces hadrons (π, K, etc) including Horn focusing is simulated using GEANT3 framework.

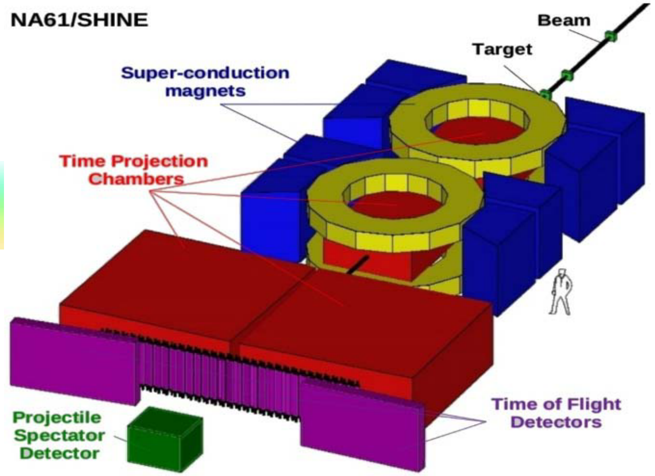
* Secondary interaction cross section is corrected using existing data by other experiments.

(3) ν producing decay is simulated. Geometrical acceptance is calculated.
→ ν flux obtained at ND & SK, respectively



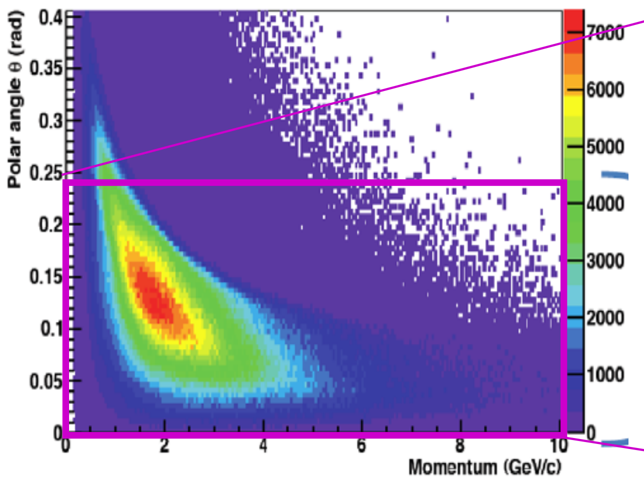


SHINE / NA61

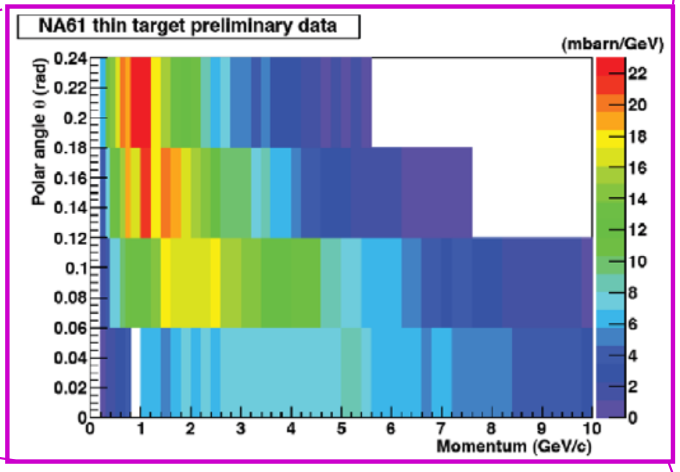


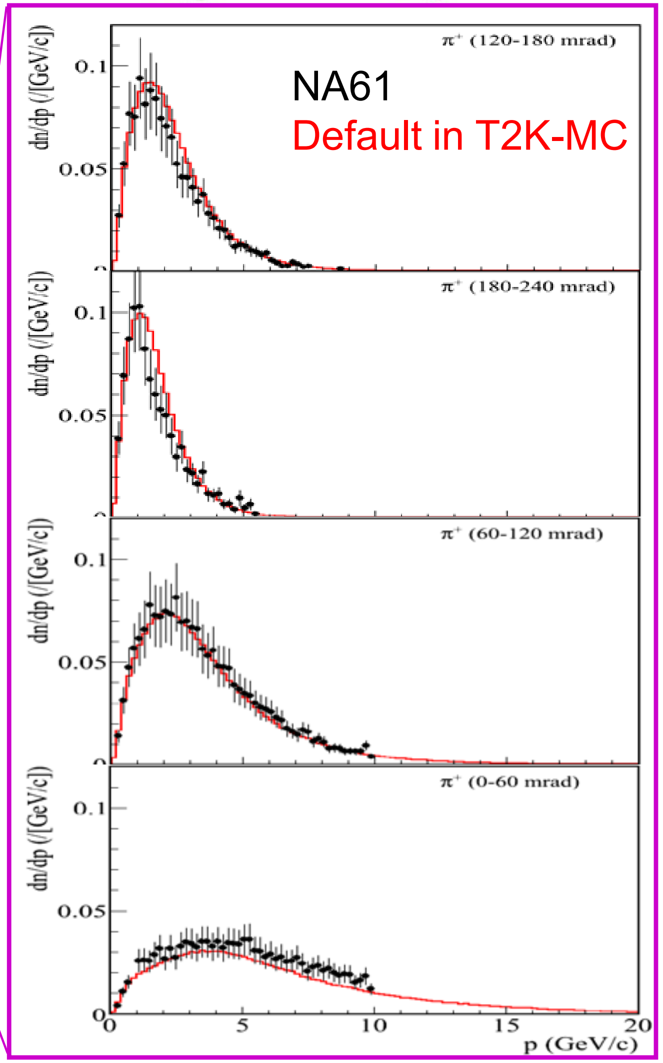
- SHINE experiment (CERN NA61)
  - Data was taken in 2007 and 2009.
    - p (30GeV) + C (target thin:2cm / thick: 90cm)
  - $\pi^{\pm}$ production model in T2K-MC is corrected by NA61 preliminary results which was released in Dec. 2009.
  - Systematic uncertainty
    - 10% : Inelastic p + C cross section
    - 20%: Pion multiplicity

MC(T2K):π^+ produce ν_μ @ SK



NA61 2007 data: π^+





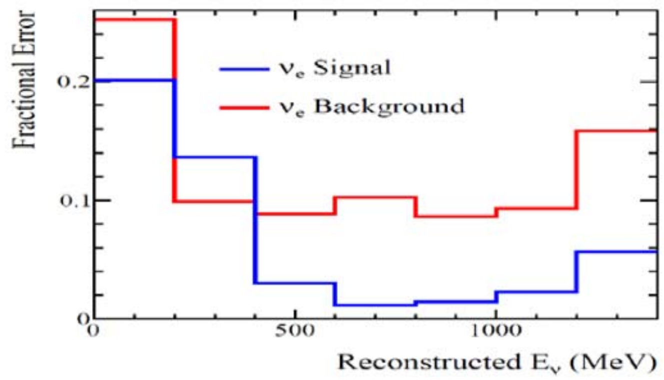
Uncertainties of ν interaction

$$N_{SK}^{expected} = (N_{ND}^{DATA} / N_{ND}^{MC}) \times (N_{SK}^{MC} + N_{bkg}^{MC})$$

~ 20% @ 400 MeV
~15% @ 600 MeV

Category	Error [%]	
CC QE	Depends on true neutrino energy	
CC 1π	30 (E_ν<2 GeV)	20 (E_ν>2 GeV)
CC coherent π	100	
CC other	30 (E_ν<2 GeV)	25 (E_ν>2 GeV)
NC $1\pi^0$	30 (E_ν<1 GeV)	20 (E_ν>1 GeV)
NC coherent	30	
NC other	30	
FSI error	Depends on reconst. neutrino energy	

Uncertainty of the ratio to CCQE



uncertainty of $\sigma(\nu e) / \sigma(\nu\mu) = 0.06$

Total uncertainty for N_{SK}/N_{ND}: ±14.2% for background
±10.2% for (signal + bkg)

@ $\Delta m_{23}^2 = 2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1.0$
$\delta_{CP}=0$
$\sin^2\theta_{13} = 0.1$ for ν_e signal

Effect of systematic uncertainty of ν flux

- # of events at SK (MC) / # of events at ND

$$N_{SK}^{expected} = (N_{ND}^{DATA} / \underline{N_{ND}^{MC}) \times (N_{SK}^{MC} + N_{bkg}^{MC})}$$

@ $\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0, \delta_{CP} = 0$
$\sin^2\theta_{13} = 0.1$ for ν_e signal

Source	(νe Sig.)/ND	(νe Bkg.)/ND	(νe Tot.)/ND
Pion Multiplicity	10.7%	5.6%	9.1%
Kaon Multiplicity	9.6%	7.2%	7.9%
Prod. Cross Sections	4.0%	0.7%	2.8%
Proton Beam	1.1%	2.1%	1.4%
ν Beam Direction	0.6%	0.6%	0.6%
Target Alignment	0.3%	0.2%	0.3%
Horn Alignment	0.2%	0.1%	0.2%
Horn Current	0.8%	0.2%	0.6%
Total	15.0%	9.4%	12.5%

Systematic error of SK efficiency

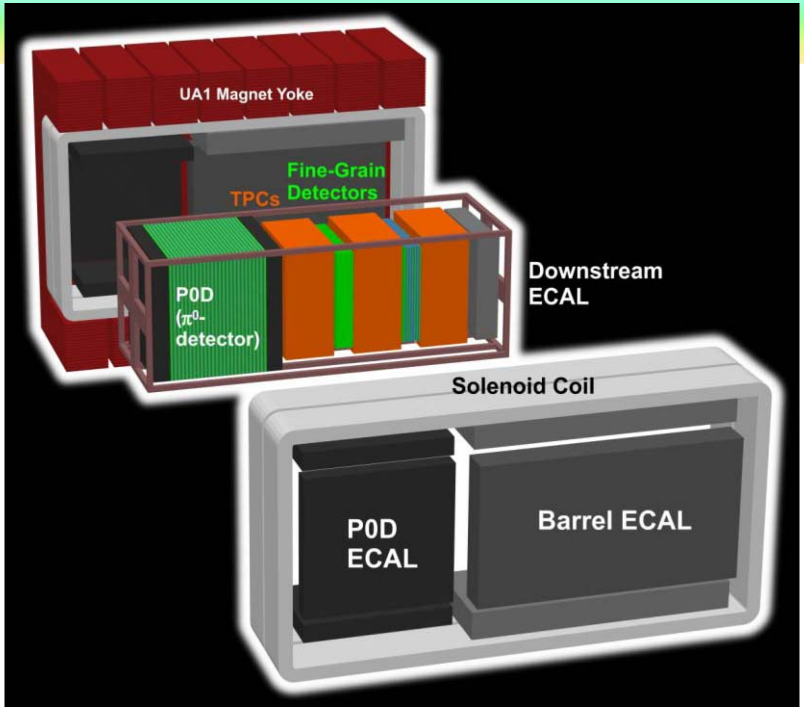
$$N_{SK}^{expected} = (N_{ND}^{DATA} / N_{ND}^{MC})\times(\underline{N_{SK}^{MC} + N_{bkg}^{MC}})$$

Parameter	Error source	Signal	Background
f^{SKnorm}	Normalization	1.4 [%]	1.4 [%]
f^{Energy}	Energy scale	0.3	0.5
$f^{N_{ring}}$	Ring counting	3.9	8.4
$f^{PID\mu}$	Muon PID	0.0	1.0
f^{PIDe}	Electron PID	3.8	8.1
f^{POLfit}	POLfit mass cut	5.1	8.7
$f^{N_{dcy}}$	Decay electron finding	0.1	0.3
$f^{\pi^0 eff}$	π^0 rejection	0.0	5.9

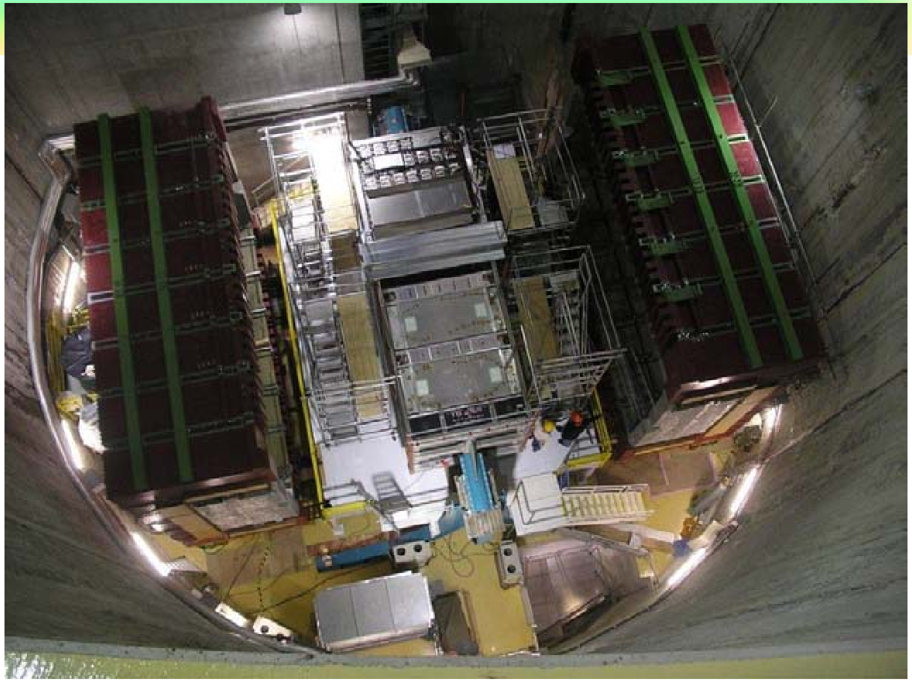
@ $\Delta m_{23}^2 = 2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1.0$
$\delta_{CP}=0$
$\sin^2\theta_{13} = 0.1$ for ν_e signal

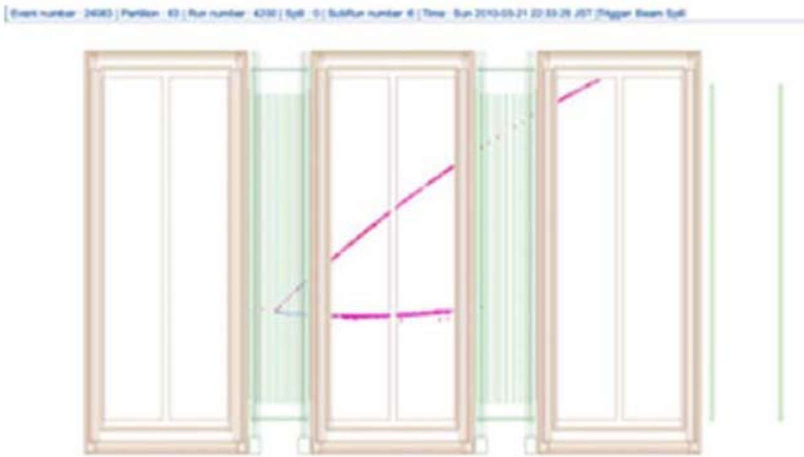
Total uncertainty: ±5.2% for signal
±12.3% for back ground

$R_{DATA/MC}$:ND280: OFF axis detector



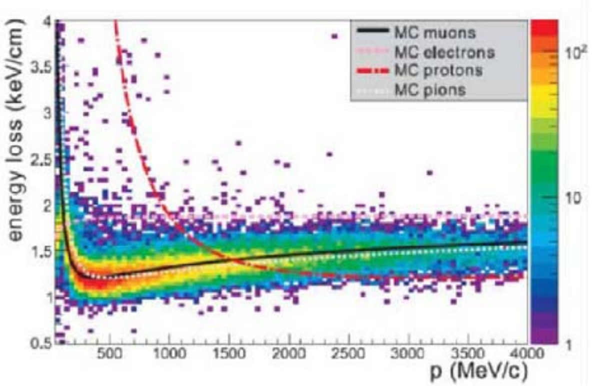
B=0.2T



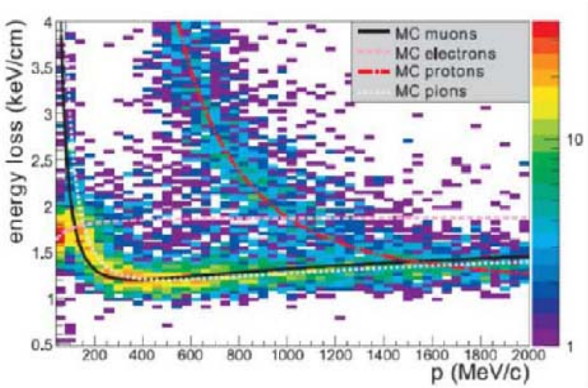


Event display of CC-candidate

TPC PID for particles from neutrino interactions

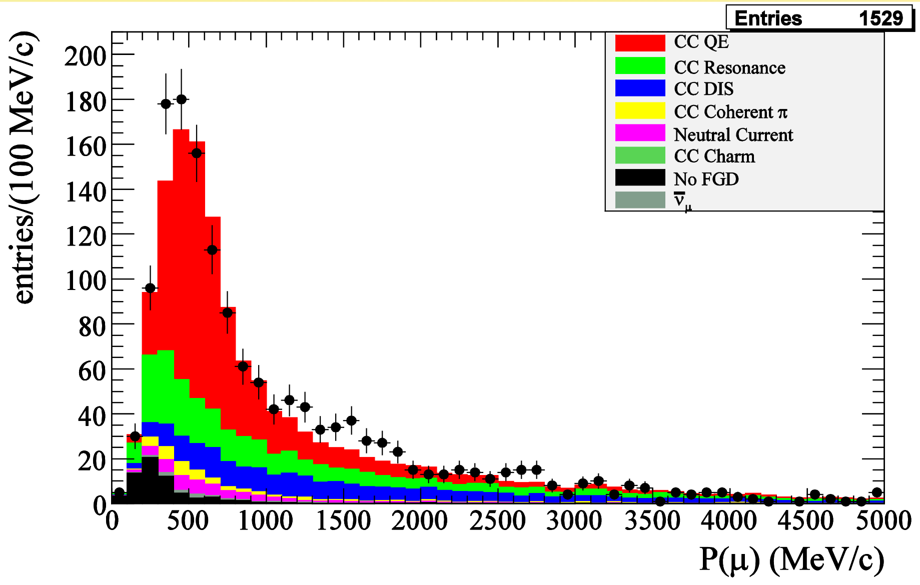


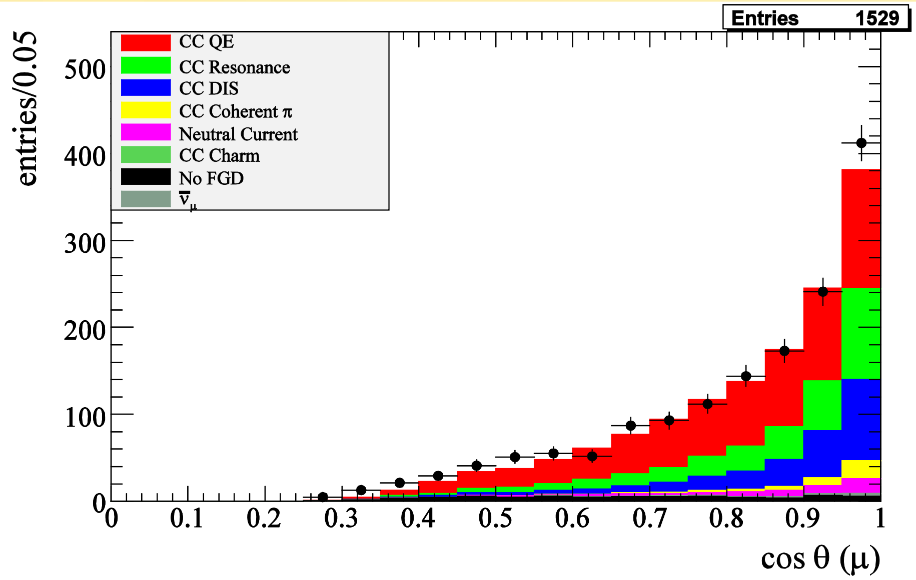
negative



positive

ND280: Normalization DATA/MC





- # of CC inclusive μ events

$$R_{DATA/MC} = 1.061 \pm 0.028\ (\text{stat})\ {}^{+0.044}_{-0.038}\ (\text{det. syst}) \pm 0.039\ (\text{phys. model})$$

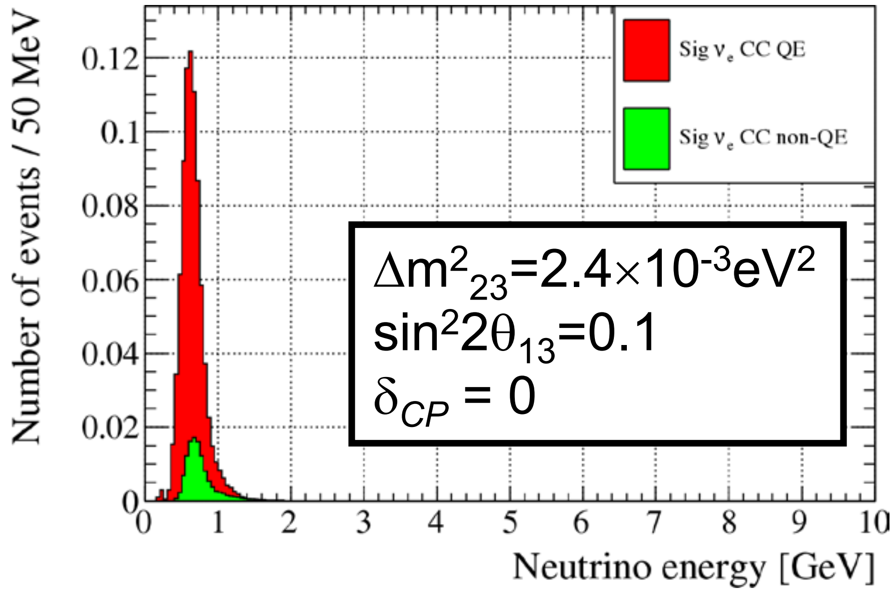
$$N_{SK}^{\text{expected}} = \left(N_{ND}^{\text{DATA}} / N_{ND}^{\text{MC}}\right) \times \left(N_{SK}^{\text{MC}} + N_{bkg}^{\text{MC}}\right)$$

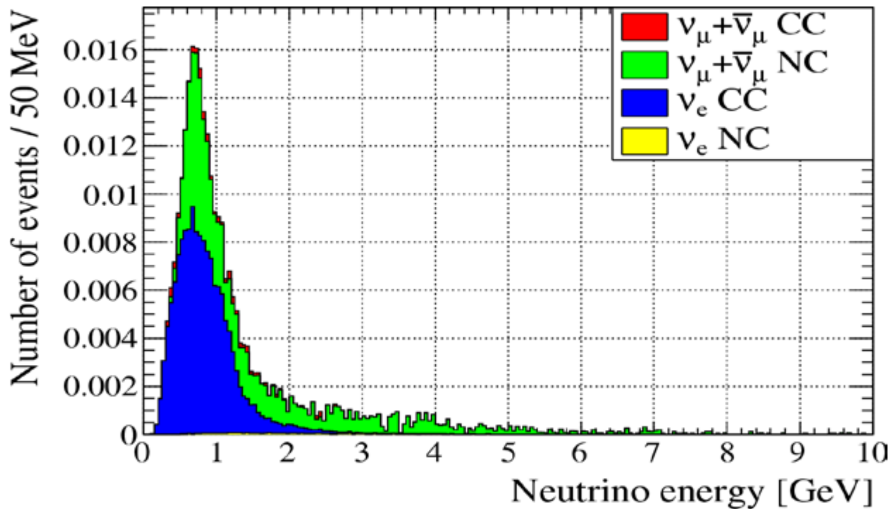
Total uncertainty for N_{SK}/N_{ND}: ±2.7% ⊕ ${}^{+5.6}_{-5.2}$ % for background

±2.7% ⊕ ${}^{+5.6}_{-5.2}$ % for (signal + bkg)

@ $\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1.0$
$\delta_{CP} = 0$
$\sin^2\theta_{13} = 0.1$ for ν_e signal

Expected # of events at SK





- $N_{SK}^{expected} = R_{DATA/MC} \times (N_{SK}^{MC} + N_{bkg}^{MC})$

# of expected Background for 3.23×10^{19}POT

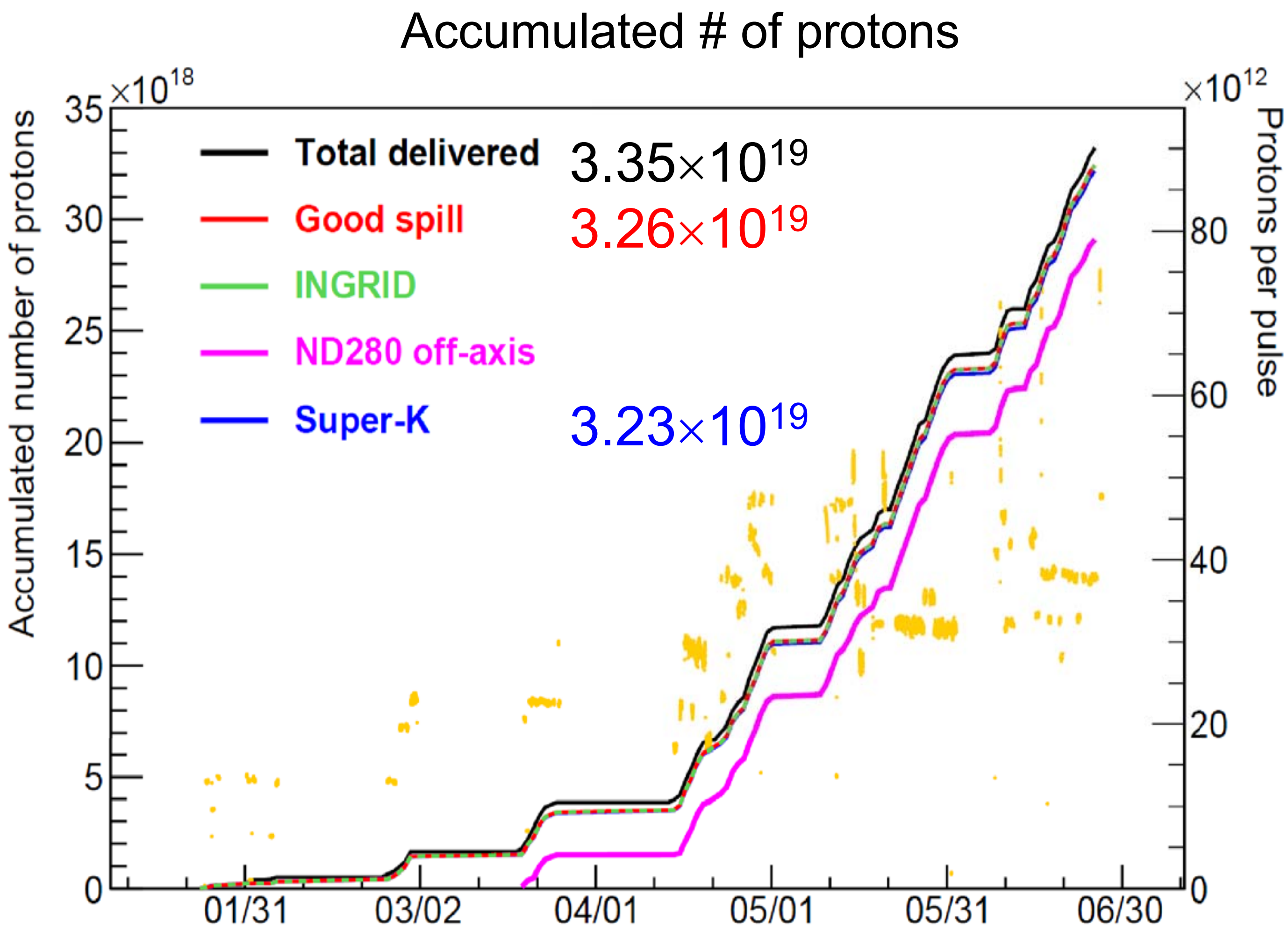
$\nu\mu$	0.13
Anti-$\nu\mu$	0.01
beam νe	0.16
Bkg total	0.30 ± 0.07 (syst.)

Sig + Bkg : 1.20 ± 0.22 (syst.)

@ $\Delta m_{23}^2 = 2.4\text{x}10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1.0$
$\sin^2\theta_{13} = 0.1, \delta_{CP}=0$ for ν_e signal

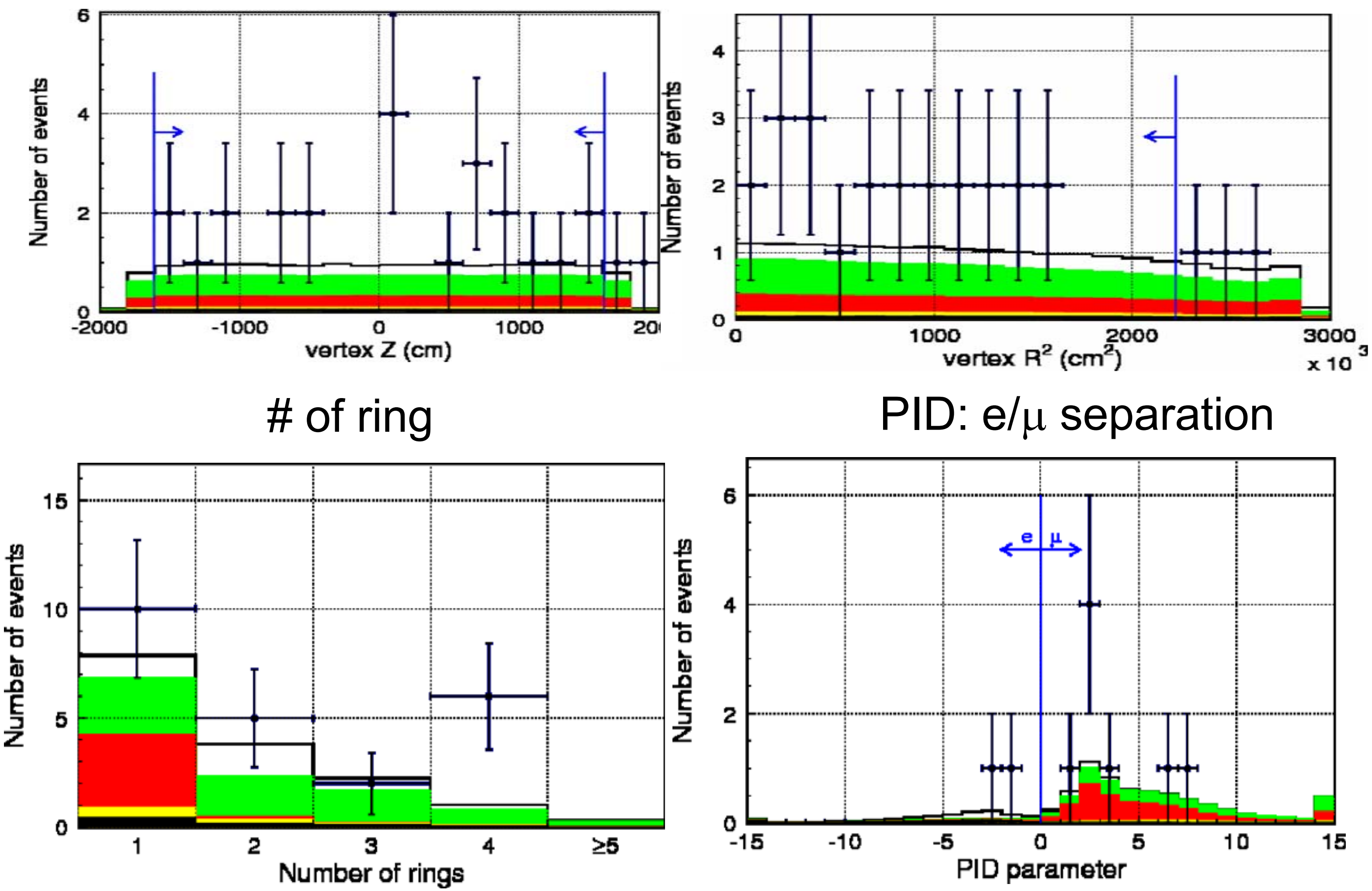
2.Select events ν_e candidate from data.

Analysis of 2010 Jan ~ Jun data



T2K event selection

Fiducial cut (Fully contained events E_{vis}>30MeV)



Histogram = MC
w/ ν oscillation
$\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2)
$\sin^2 2\theta_{23} = 1.0$
$\sin^2 2\theta_{13} = 0.0$,
POT normalized

CC-QE(red)
CC non-QE
Anti-$\nu\mu$ (yellow)
ν_e (black)
NC (white)

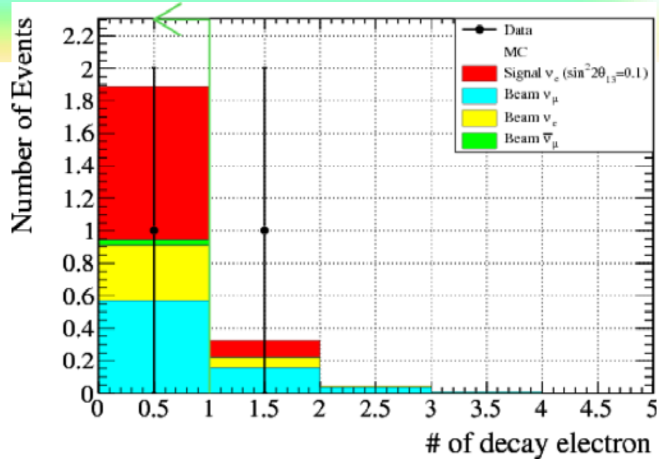
T2K event selection

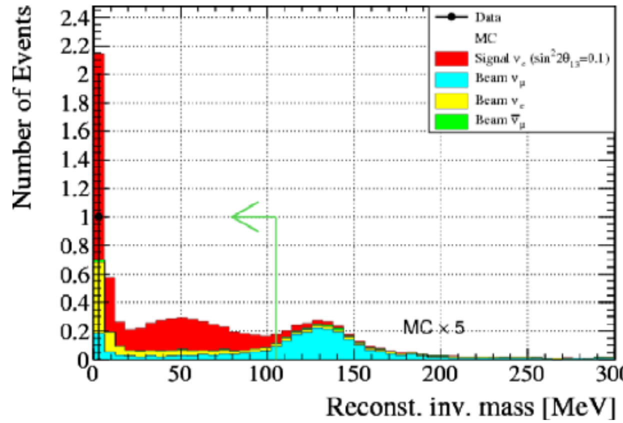
"good beam spill" accepted by SK = 3.23×10^{19} POT

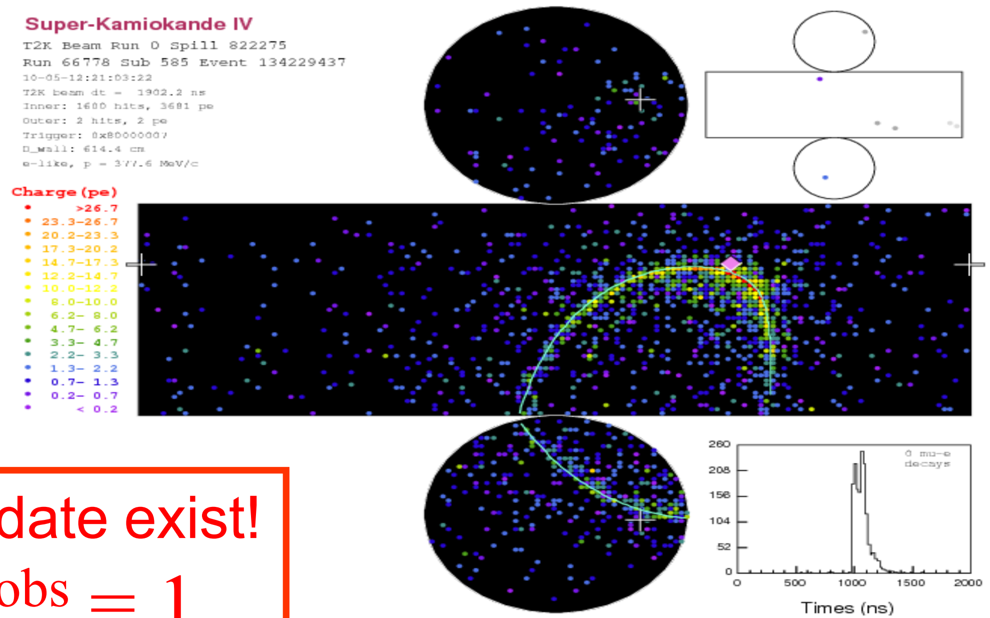
	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$ $\sin^2 2\theta_{13} = 0.0$
Fully-Contained	**33**	54.5	24.6
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7
Single-ring μ-like (P_μ>200MeV/c)	**8**	24.5 ±3.9	7.1 ±1.3
Single-ring e-like (P_e>100MeV/c)	**2**	1.5 ±0.7	1.3 ±0.6
Multi-ring	**13**	10.2	8.0

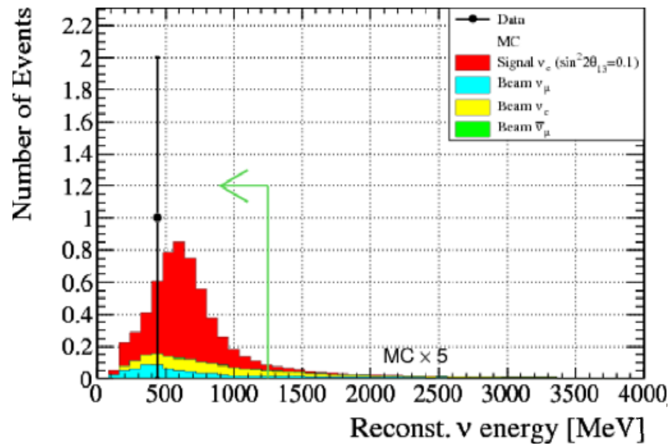
Background rejection for ν_e appearance

- # of decay electron ($\mu \rightarrow e + \nu_e$) =0
  - Reject $\nu\mu$ contamination : 1 event rejected.
- Reconstructed invariant mass assuming 2γ rings exist <105MeV
  - Reject π^0
- Reconstructed ν energy < 1250 MeV
  - Oscillation maximum at ~600 MeV









1 candidate exist!

$$N_{SK}^{obs} = 1$$

3.Estimate the oscillation parameter.

Estimation of oscillation parameter

Upper bound of θ_{13} are evaluated by 2 independent method.

A: Feldman-Cousins
B: Classical one-sided limit

Systematic uncertainties are took into account for both analysis.

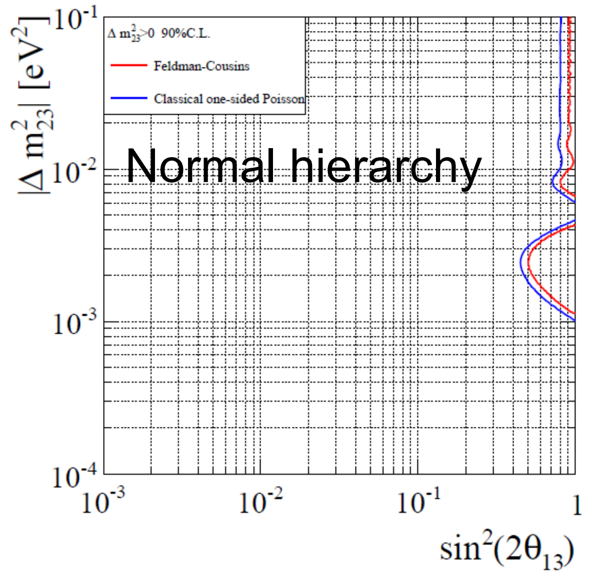
90% CL upper limit at $\Delta m^2_{23}=2.4\times10^{-3}\mathrm{eV}^2$, δ_{CP} = 0

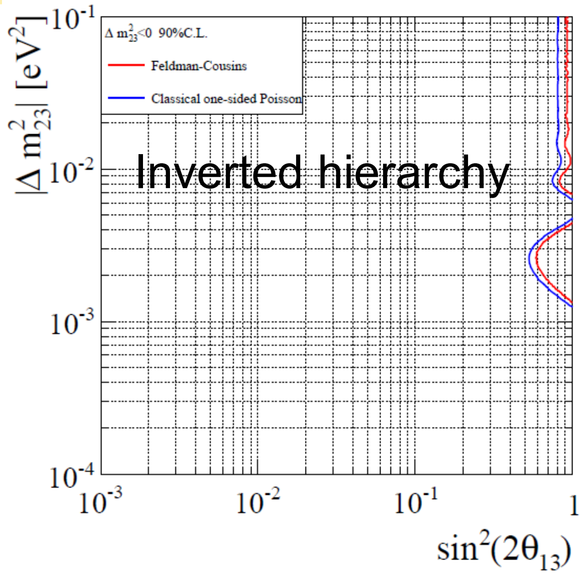
A

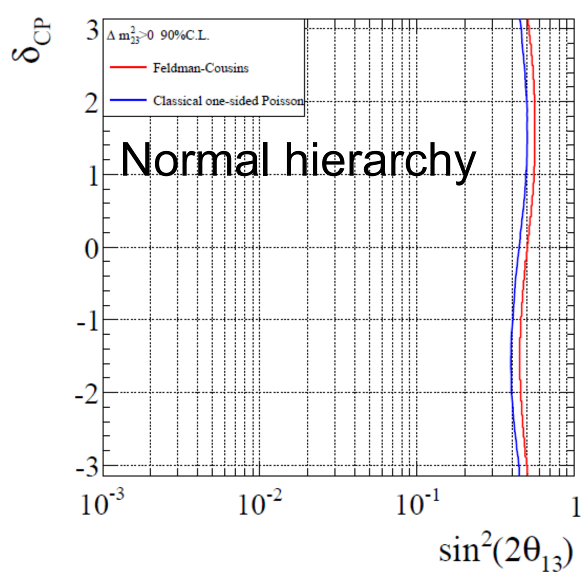
Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.50	0.35
Inverted ($\Delta m^2_{23} < 0$)	0.59	0.42

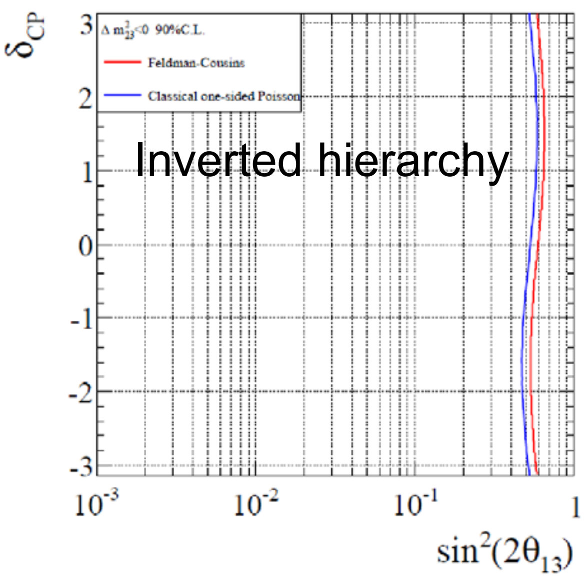
B

Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.44	0.32
Inverted ($\Delta m^2_{23} < 0$)	0.53	0.39





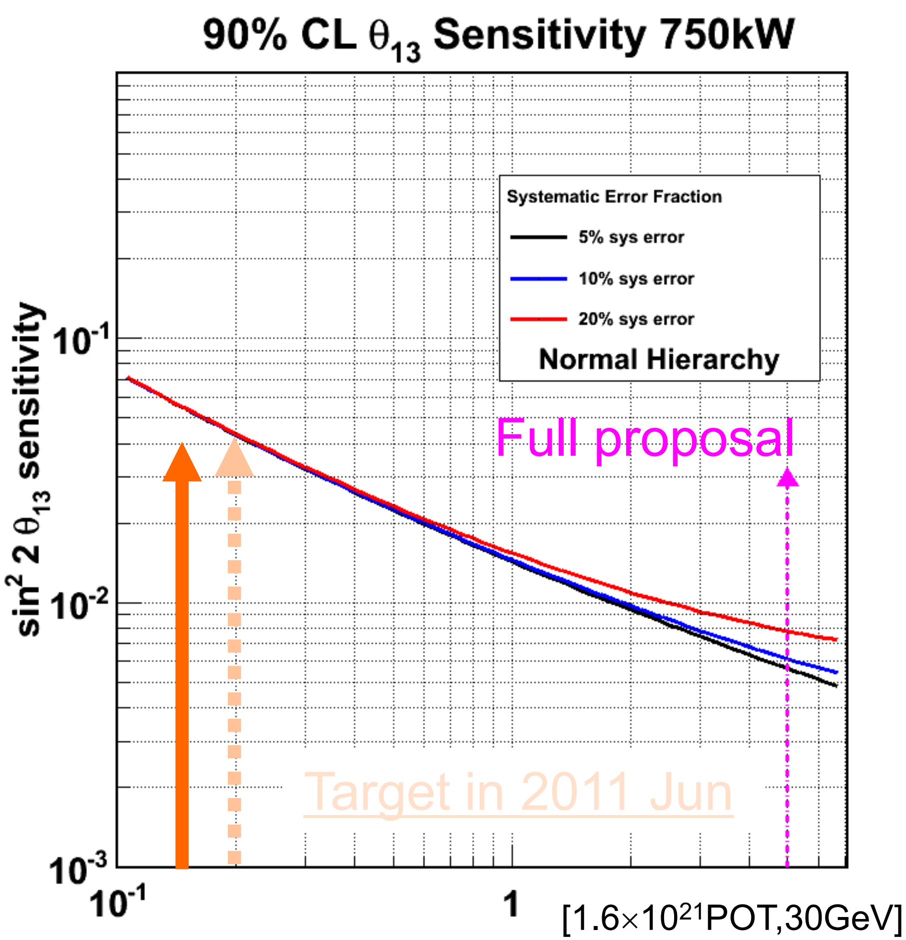




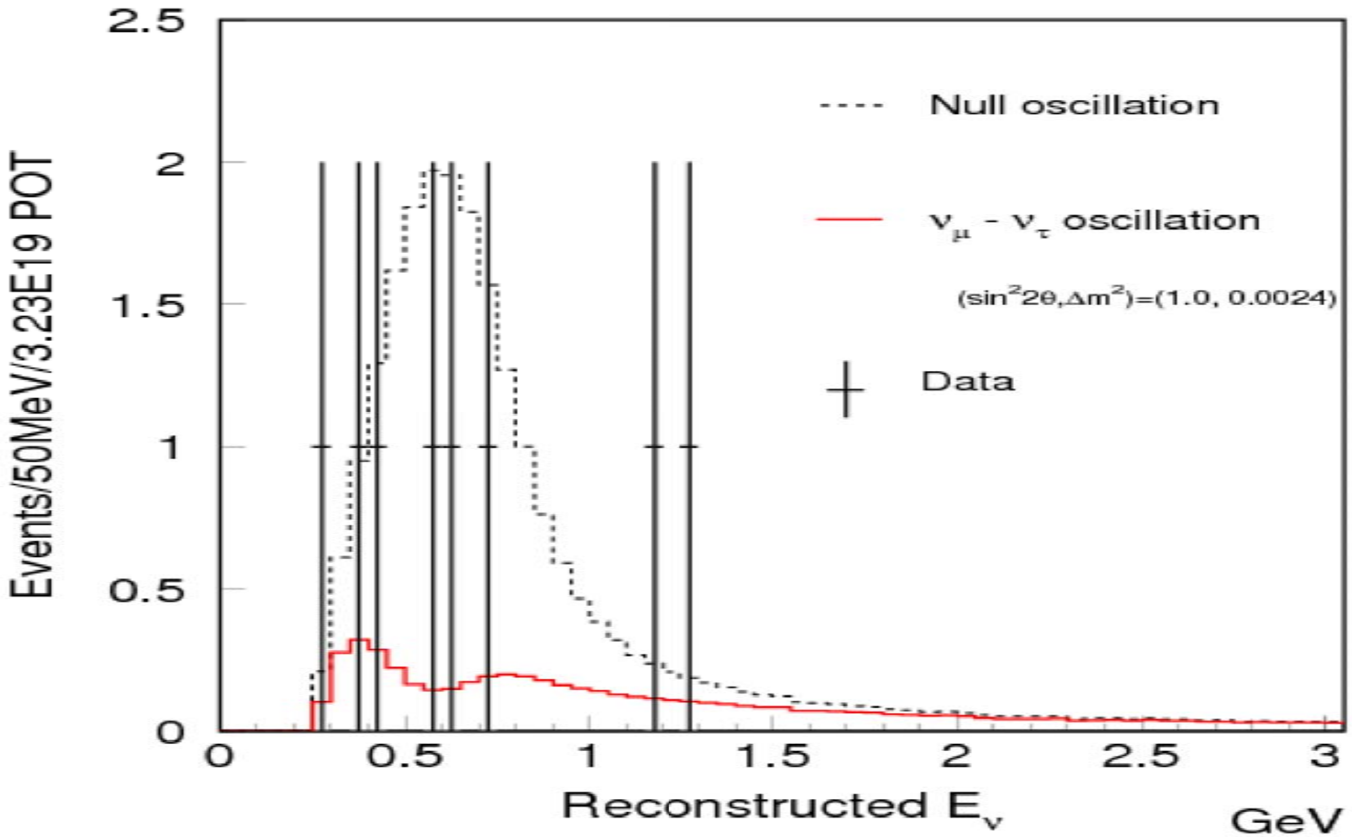
Prospects in 2011

- Analyze all the available data:
  - 1.45×10^{20} POT
  - The statistics is ~1/2 of the target by 2011 june which is planned in last summer: 3×10^{20} POT=150kW $\times10^{7}$s

  $\rightarrow$ Data size become about $\times4$.
- Possible analysis improvements
  - New NA61 results is available. → Systematic uncertainty from hadron production can be reduced.
  - Spectrum measurement in ND



ν_μ disappearance analysis



- 8 ν_μ events observed.
- # of events agree with MINOS / SK measurements.

Summary

- T2K searches for $\nu_\mu \rightarrow \nu_e$ oscillation and determines ν oscillation parameter: θ_{13}.
- T2K start physics run from Jan. 2010. Integrated POT so far is 1.45×10^{20}.
- $\nu_\mu \rightarrow \nu_e$ oscillation analysis using 3.23×10^{19} (2010 Jan. ~ Jun) is reported.
  - # of expected background is 0.30 ± 0.07.
  - # of observed events is 1.
- Observed ν_μ events are consistent with the neutrino oscillation measured by SK, K2K and MINOS.