Status of the T2K experiment

K. Matsuoka (Kyoto Univ.)
for the T2K collaboration

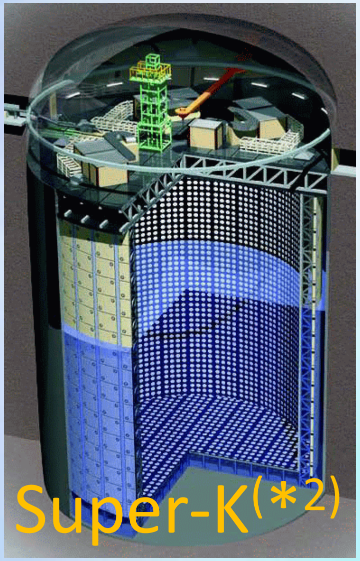
Contents

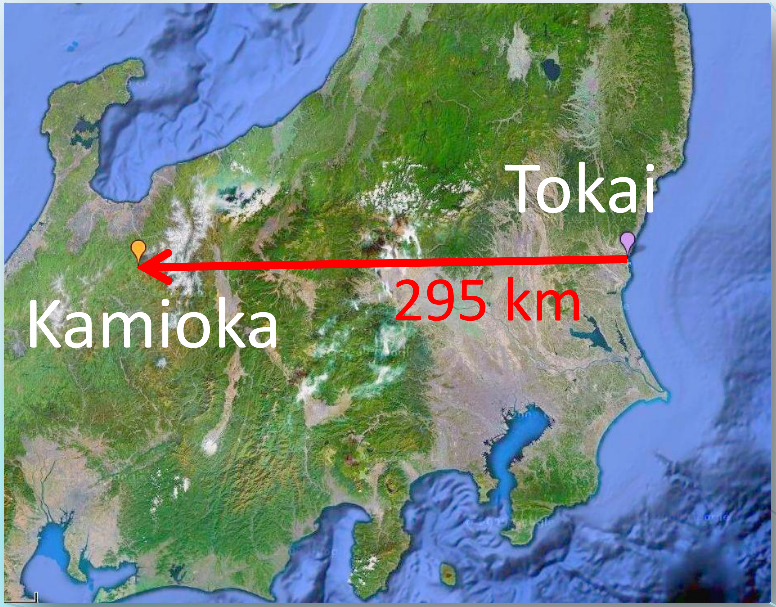
- Physics motivations (neutrino oscillation)
- Concept of the T2K experiment
- Beam commissioning results

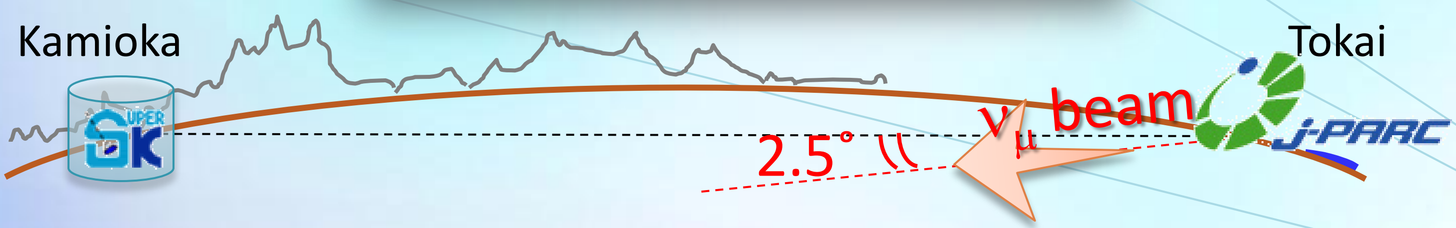
The T2K (Tokai-to-Kamioka) experiment

50-kt water cherenkov

30-GeV 750-kW proton beam







- **Search for $\nu_\mu \rightarrow \nu_e$** ($\nu_e$ appearance)
- **Precise measurement of $\nu_\mu \rightarrow \nu_x$** ($\nu_\mu$ disappearance)

*1 Japan Proton Accelerator Research Complex *2 The Super-KAMIOKANDE detector. See Yamada-san's talk

T2K collaboration

- 12 countries (Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, USA)
- ~500 collaborators from 62 institutions

Neutrino oscillation

- Neutrino changes its flavor while propagating in vacuum/matter.
  → Neutrinos have masses = **Evidence for physics beyond the Std. Model.**

Flavor eigenstates: ν_e, ν_μ, ν_τ

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

Mass eigenstates: m_1, m_2, m_3

Atmospheric & accelerator — Reactor & accelerator — Solar & reactor

$$U_{\mathrm{MNS}} = \begin{pmatrix}1 & 0 & 0\\ 0 & +c_{23} & +s_{23}\\ 0 & -s_{23} & +c_{23}\end{pmatrix}\begin{pmatrix}+c_{13} & 0 & +s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & +c_{13}\end{pmatrix}\begin{pmatrix}+c_{12} & +s_{12} & 0\\ -s_{12} & +c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \approx \begin{pmatrix}0.8 & 0.5 & s_{13}e^{-i\delta}\\ 0.4 & 0.6 & 0.7\\ 0.4 & 0.6 & 0.7\end{pmatrix}$$

$\theta_{23} = 37^\circ \sim 45^\circ$
$\Delta m_{23}{}^2 \approx 2.4 \times 10^{-3}$ eV^2

$\theta_{13} < 10^\circ$ by CHOOZ

$\theta_{12} \approx 34.4^\circ \pm 1.3^\circ$
$\Delta m_{12}{}^2 \approx 8 \times 10^{-5}$ eV^2

$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$
$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

- Mass hierarchy ($m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$)?
- Size of the mixing angle θ_{13}?
- Size of the CP phase δ? … Ability to measure CP violation depends on $\sin\theta_{13}$.

→ Important to measure θ_{13}.

Concept of T2K

- **Probability of $\nu_\mu \rightarrow \nu_x$ (θ_{23}, Δm_{23}^2)**

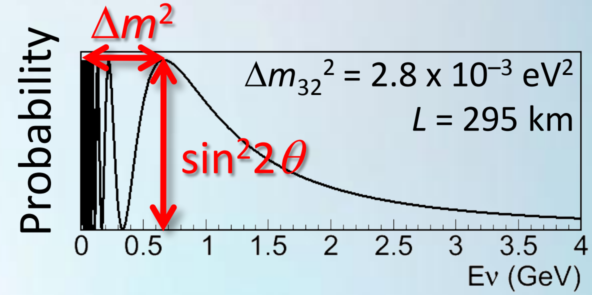
$$P(\nu_\mu \rightarrow \nu_x) \approx \sin^2 2\theta_{23} \sin^2\left(\Delta m_{32}^2 L / 4E_\nu\right)$$

- **Probability of $\nu_\mu \rightarrow \nu_e$ (θ_{13})**

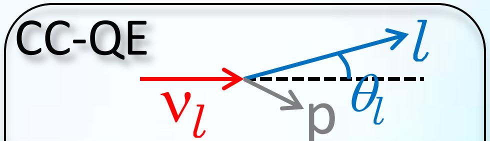
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\Delta m_{32}^2 L / 4E_\nu\right)$$

295 km

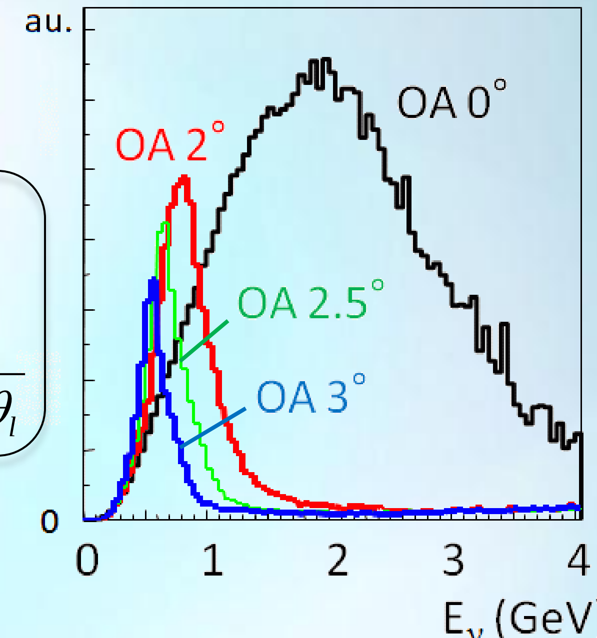
$\sin^2 2\theta_{13}$ < 0.13, $\sin^2\theta_{23}$ ~0.5



- CC-QE(*) events to measure E_ν
- Off-axis beam configuration
  - Adjust E_ν to ones around the oscillation max.
  - Reduce high energy νs' B.G. from non CC-QE.

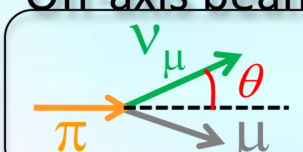


$$E_\nu \approx \frac{m_n E_l - m_l^2/2}{m_n - E_l + p_l \cos\theta_l}$$



- High statistics
  - J-PARC + Super-K + off-axis beam
  - Expected event rate in Super-K:
    ~700 CC interactions (for 750 kW x 10^7 sec)
- Far-to-near flux extrapolation
  - Measure ν flux, energy and flavor both at the near (ND280) and the far (Super-K) detectors.

Off-axis beam



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

* CC-QE: Charged Current Quasi-Elastic

Measurement of $\nu_\mu \rightarrow \nu_x$

$$P(\nu_\mu \rightarrow \nu_x) = N_\nu^{\mathrm{obs}} / N_\nu^{\mathrm{null}}(E_\nu) \approx \sin^2 2\theta_{23} \sin^2\left(\Delta m_{32}^2 L / 4E_\nu\right)$$

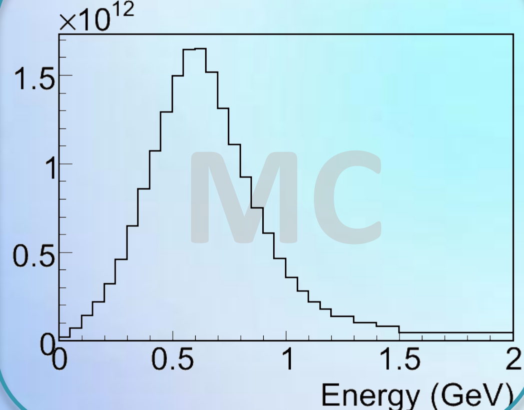
$N_\nu^{\mathrm{null}} = R \times \Phi_\nu^{\mathrm{ND}} \times \sigma_\nu^{\mathrm{water}}$

Uncertainty is reduced by
- ND280 for Φ_ν^{ND} and $\sigma_\nu^{\mathrm{water}}$
- Beam monitoring for R

R(Far/Near)
Extrapolation by MC which is experimentally verified by NA61(*)

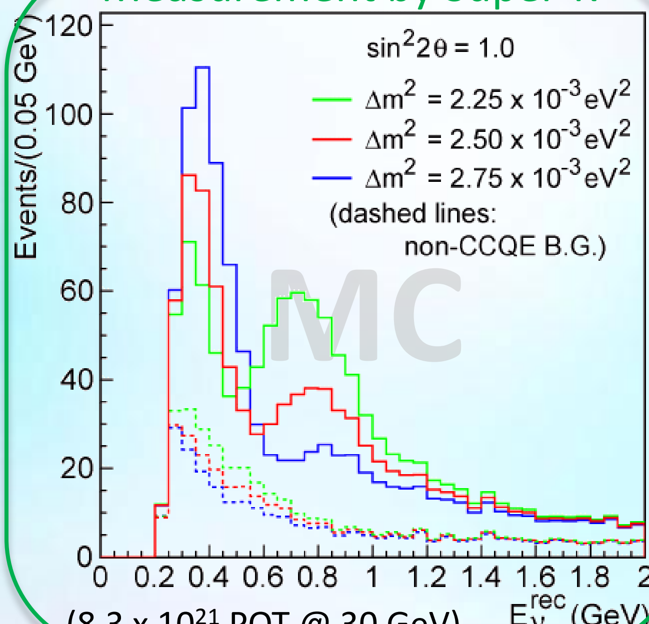
Φ_ν^{ND}

Measurement by ND280



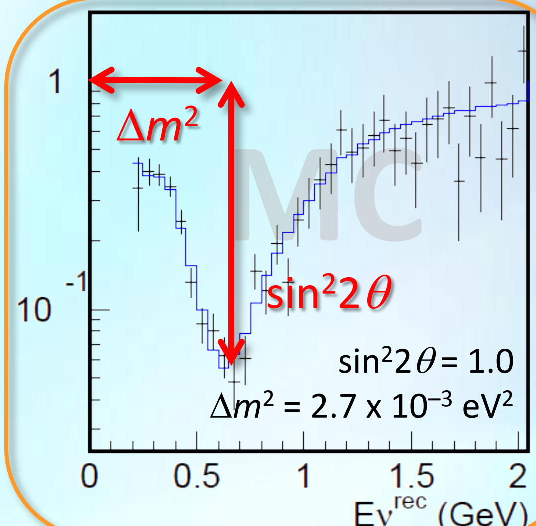
N_ν^{obs}

Measurement by Super-K



(8.3 x 10^21 POT @ 30 GeV)

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



Target — ND280 — Super-K

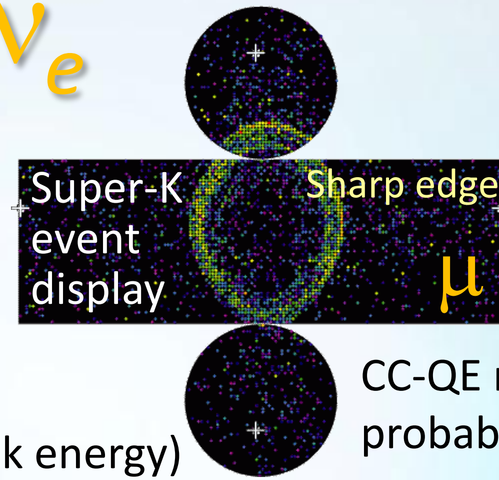
0 m — ~280 m — 295 km

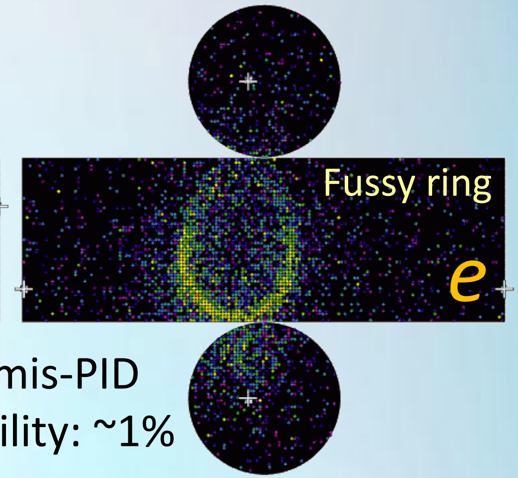
* See Nicolas' talk

Accurate prediction of N_ν^{null} is important to measure θ_{23} and Δm_{32}^2 precisely.

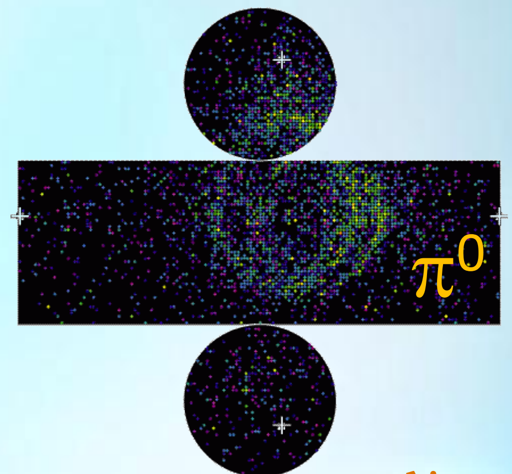
Search for $\nu_\mu \rightarrow \nu_e$

- ν_e signal
  - 1-ring e-like event (CC-QE)
- Background
  - Beam ν_e contamination
    (~0.4% of ν_μ at ν_μ spectrum peak energy)
  - Mis-reconstructed NC(*1) π^0 event(*2)
    (mainly from high E νs ← reduced by the off-axis beam)

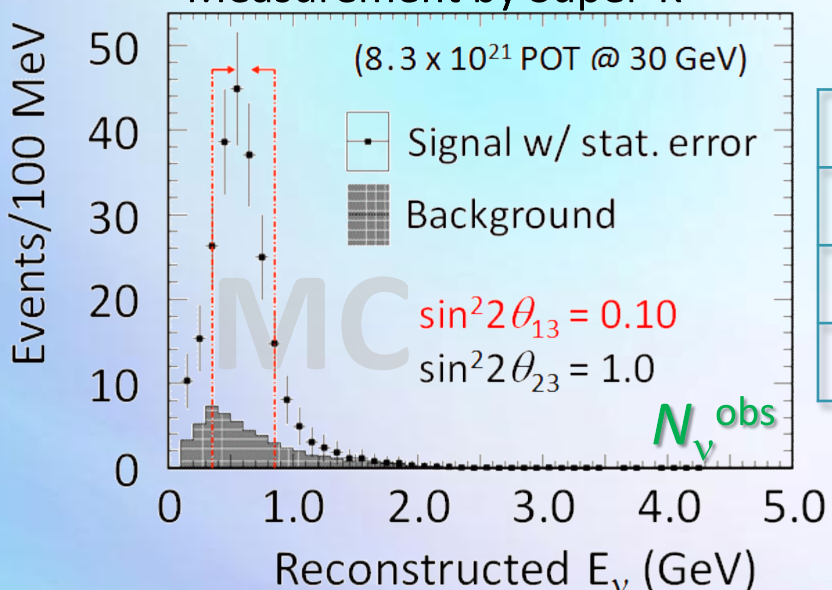




CC-QE mis-PID probability: ~1%



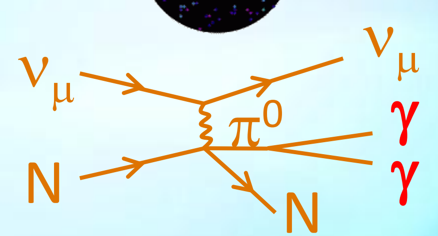
Measurement by Super-K



Expected num. of events in 0.35-0.85 GeV

$\sin^2 2\theta_{13}$	**0.1**	**0.01**
Signal	143	14
Beam ν_e BG	16	16
BG from ν_μ	10	10

($\sin^2 2\theta_{13} < 0.13$ by CHOOZ)

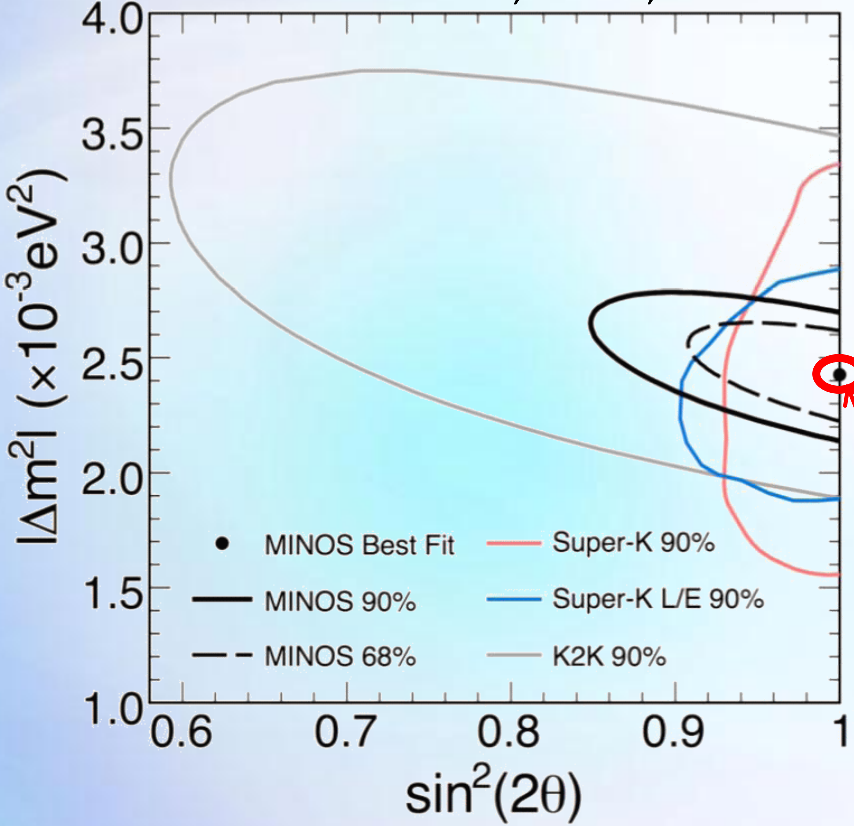


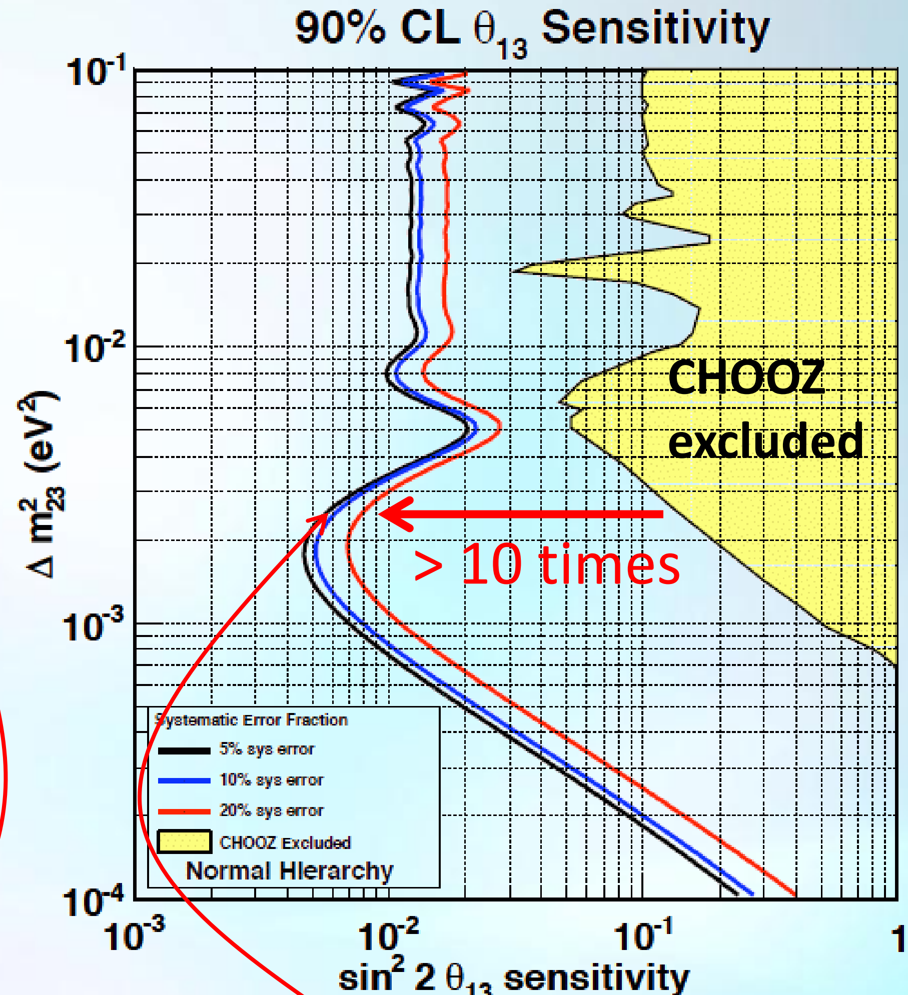
*1 NC: Neutral Current *2 See Joshua's talk

T2K sensitivity

30 GeV, 8.3 x 10^{21} POT, $\delta_{CP} = 0$

M.Diwan, Venice, Mar.2009





$\delta(\sin^2 2\theta_{23}) \approx 0.01$, $\delta(\Delta m_{23}^2) < 10^{-4}$ eV^2

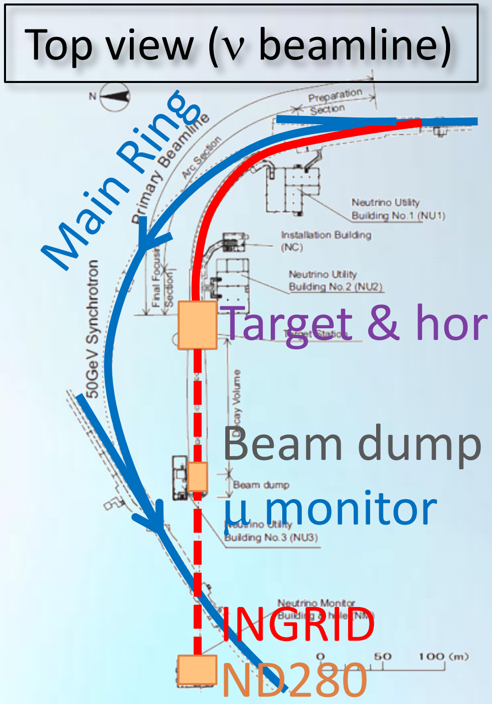
0.0060 @ $\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV^2
(for a 10% sys. error)

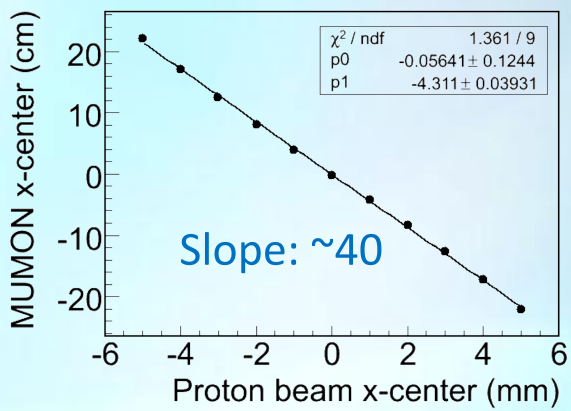
T2K neutrino beam

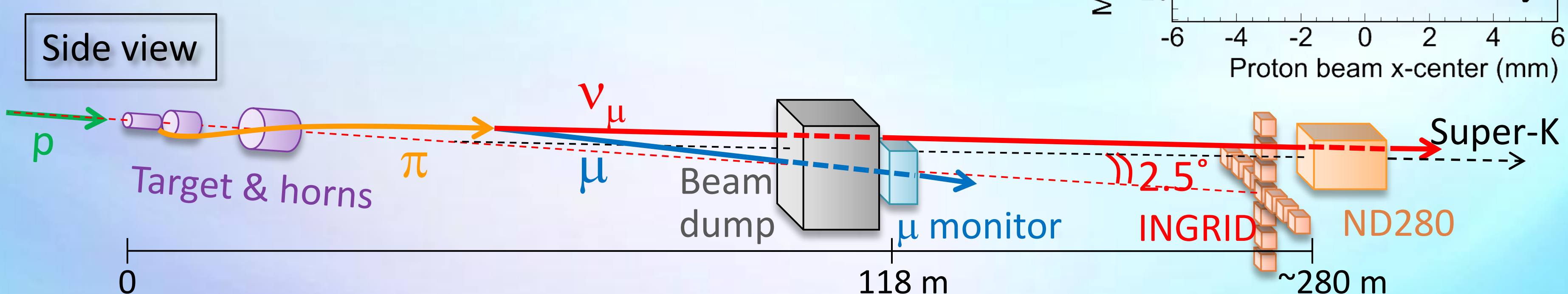
- High power beam
  - Beam loss has to be held as low as possible.
  - Shift of the proton beam on the target makes a shift of the ν beam direction.

  → Necessary to tune and monitor the proton beam.
- Off-axis beam configuration
  - E_ν spectrum peak shifts according to the ν beam direction (ΔE_{peak} = 2%/mrad).

  → Necessary to tune and monitor the ν beam direction precisely (w/in 1 mrad).



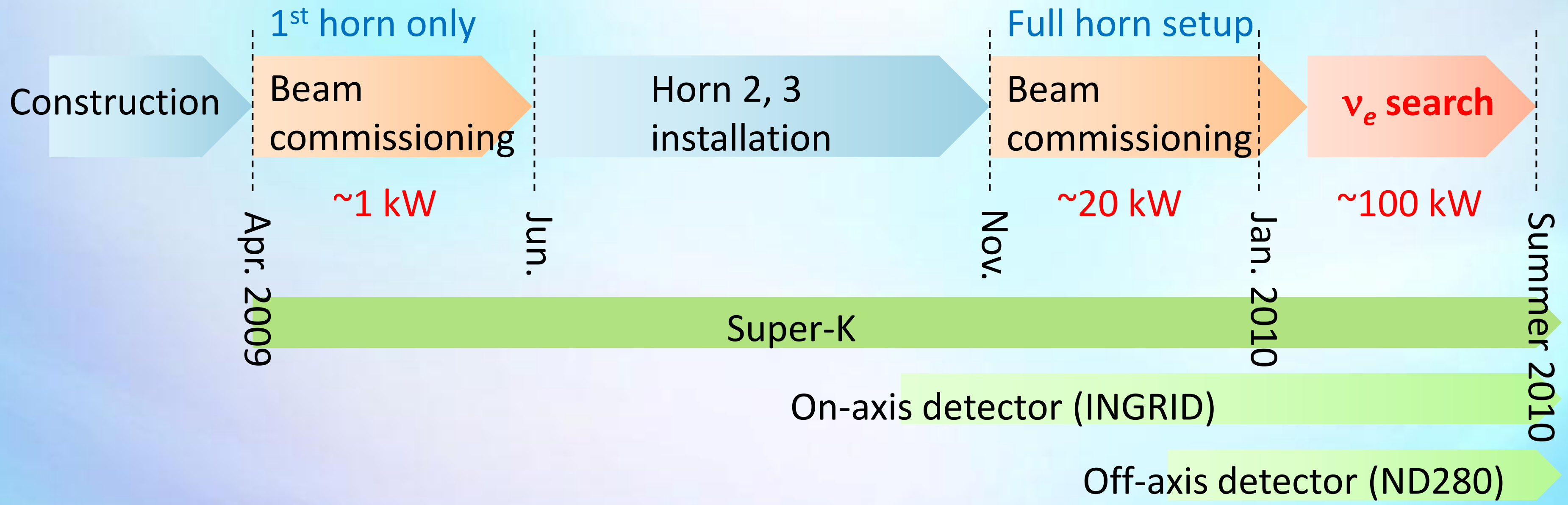




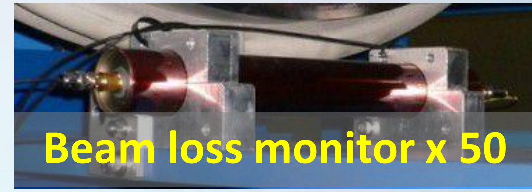
Beam commissioning

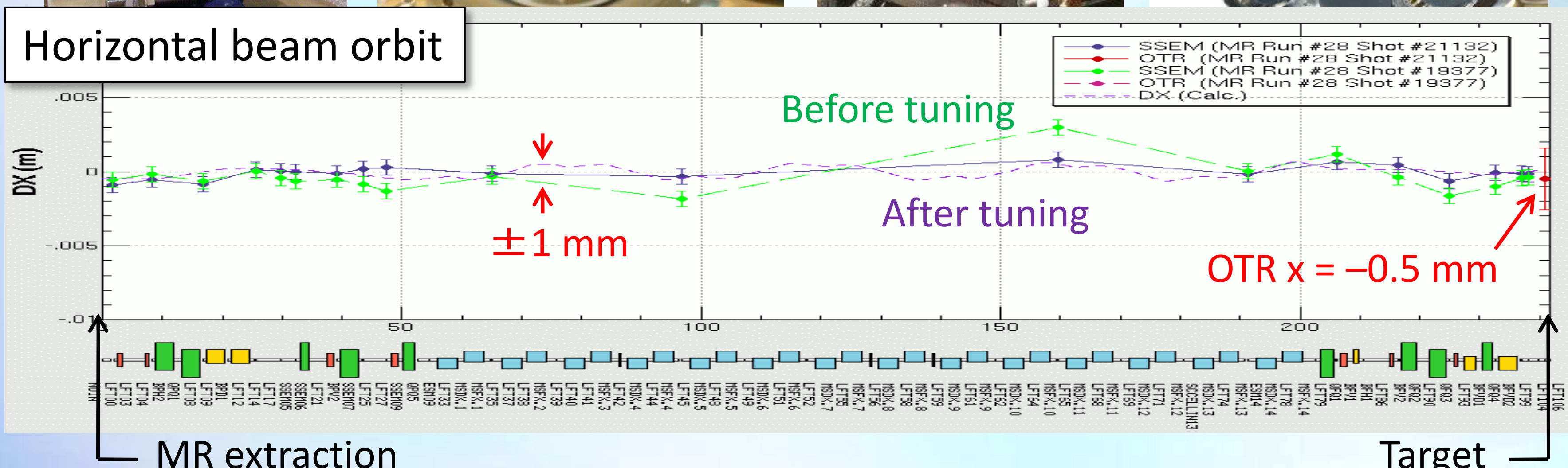
- Purpose
  - Check all components (the magnets, beam monitors, horns, DAQ, etc.) work as expected.
  - Tune the proton beam orbit and the pos./size at the target.
  - Tune the ν beam direction by the muon monitor and INGRID.
  - Establish operation of the ν detectors (ND280 and Super-K).

→ ν_e appearance search started.



Proton beam monitors



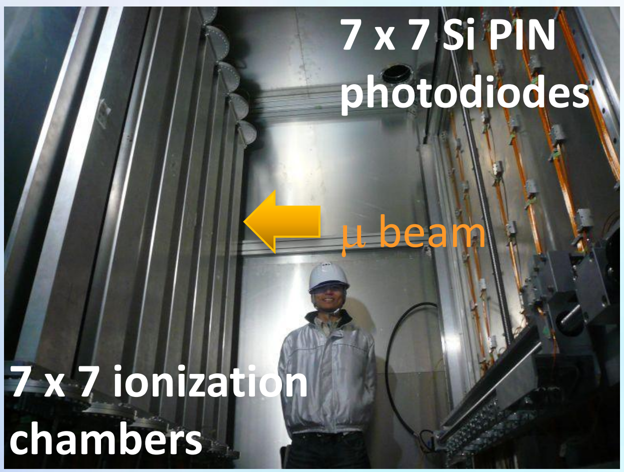


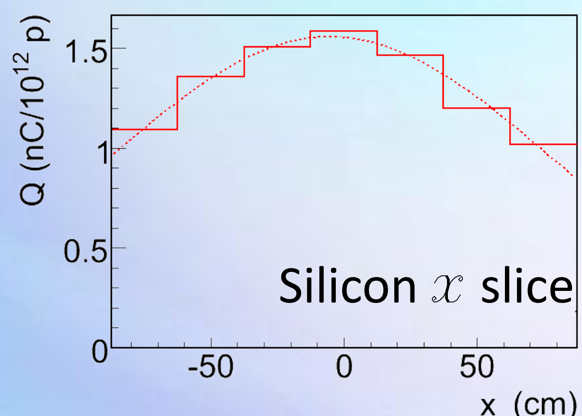
- Proton beam orbit was tuned by using the proton beam monitors.
  - Deviation of the orbit from the beam line is less than 1 mm.
  - The beam loss is enough small.
  - Proton beam hits the center of the target.

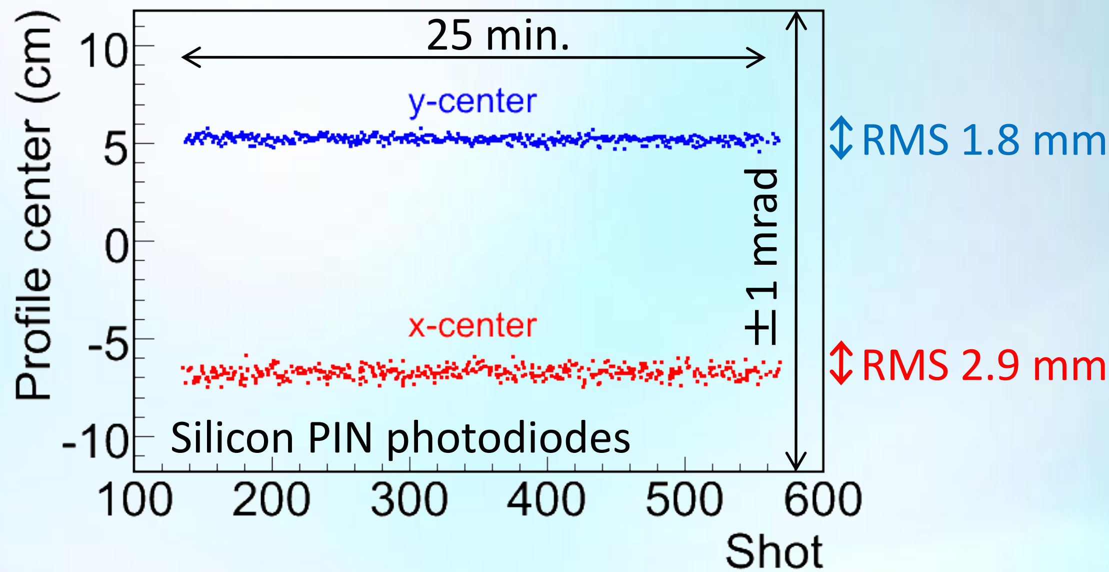
Muon monitor

Required precision of the profile center:
Better than 11.8 cm (= 1 mrad) → **3 cm**

- Monitor the neutrino beam flux and direction on a shot-by-shot basis by measuring the muon profile.
  - Measures ionization yield by muons at each sensor to reconstruct the profile.
  - Beam direction is a direction from the target to the profile center.





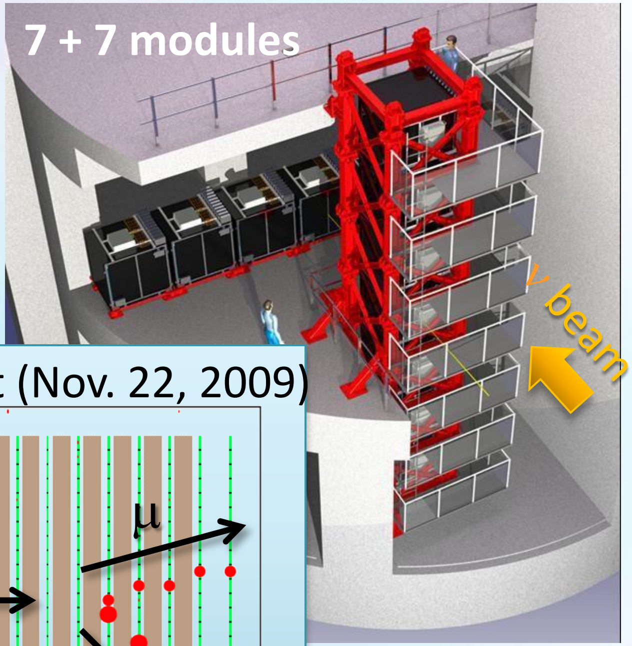


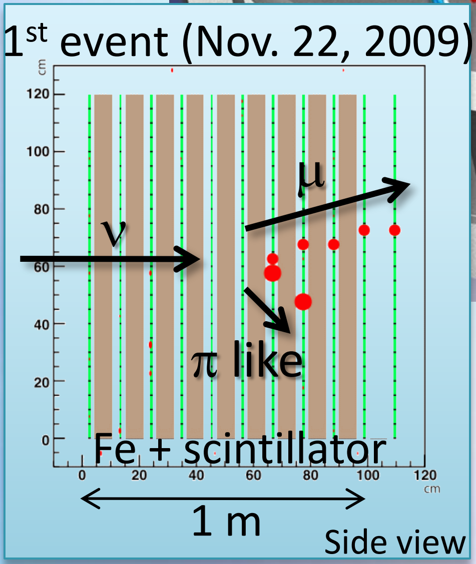
- No time dependent drift.
- Further beam tuning was ongoing at this time.

Muon monitor measures the beam direction stably w/ a precision much better than 1 mrad.

Neutrino beam monitor (INGRID)

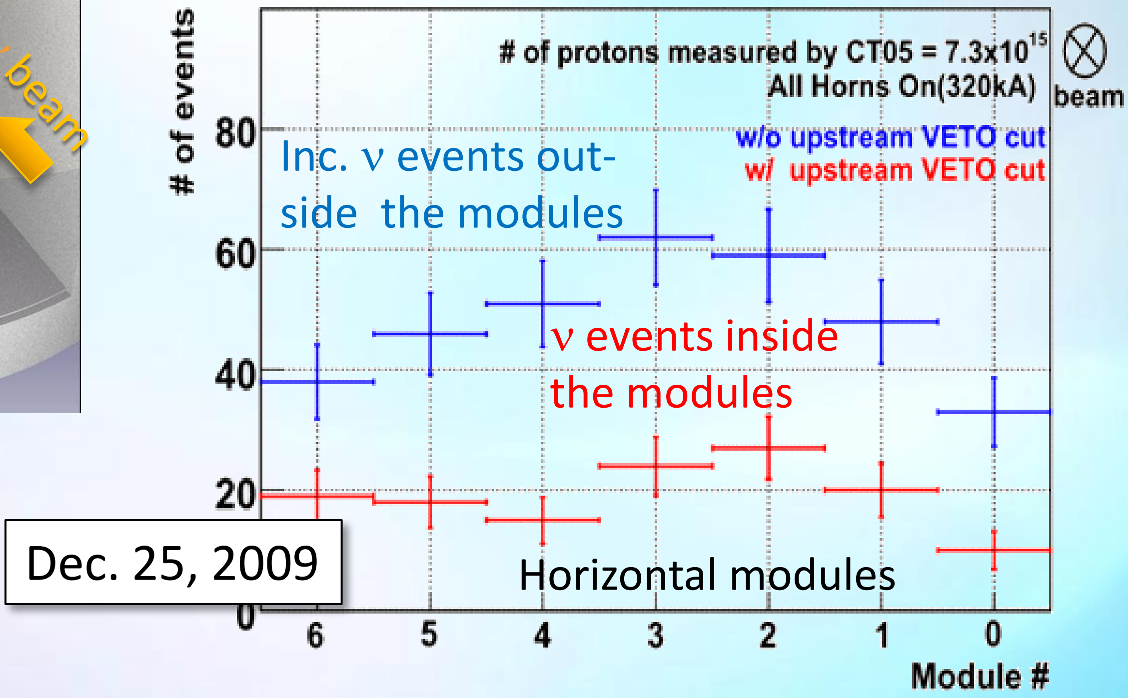
- Monitor the neutrino beam flux and direction w/ ~1-day statistics by measuring the on-axis neutrino profile.
  - Counts neutrino (CC-QE) events in each module to reconstruct the profile.





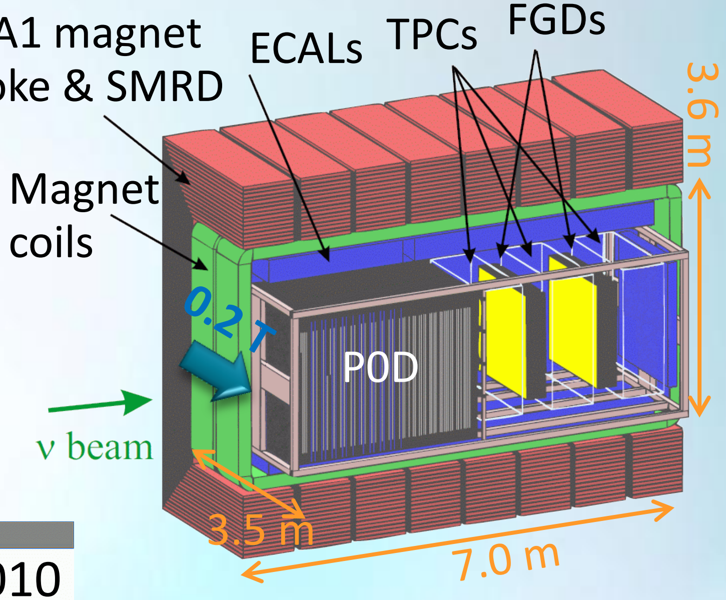
Required precision of the profile center:
Better than 28.0 cm (= 1 mrad) → **5 cm**

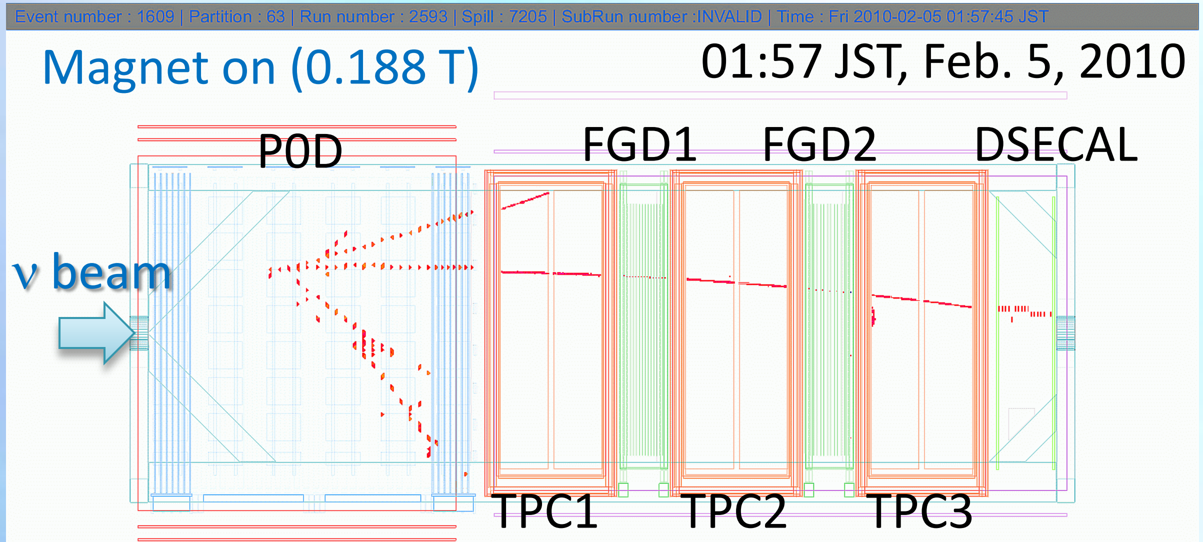
Event rate of each module for 7.3 x 10^{15} POT



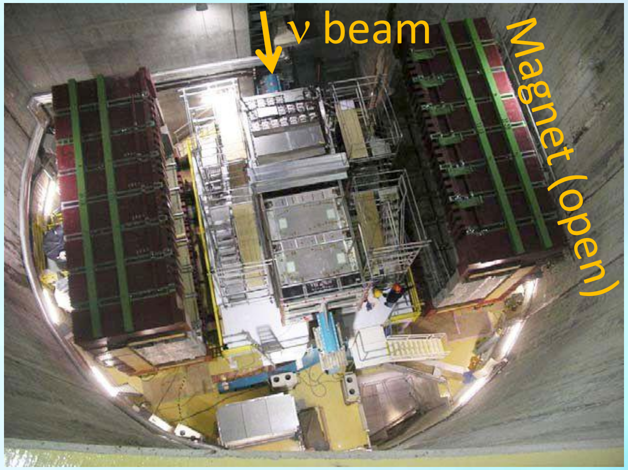
Neutrino event in ND280

- Measure Φ_{ν}^{ND} and σ_{ν}
  - P0D: π^0 Detector → NC π^0 rate
  - TPC: Time Projection Chamber → PID (dE/dx)
  - Magnetic field 0.2 T } p_l
  - FGD: Fine Grain Detector → θ_l
  - ECAL: Electromagnetic CALorimeter
  - SMRD: Side Muon Range Detector



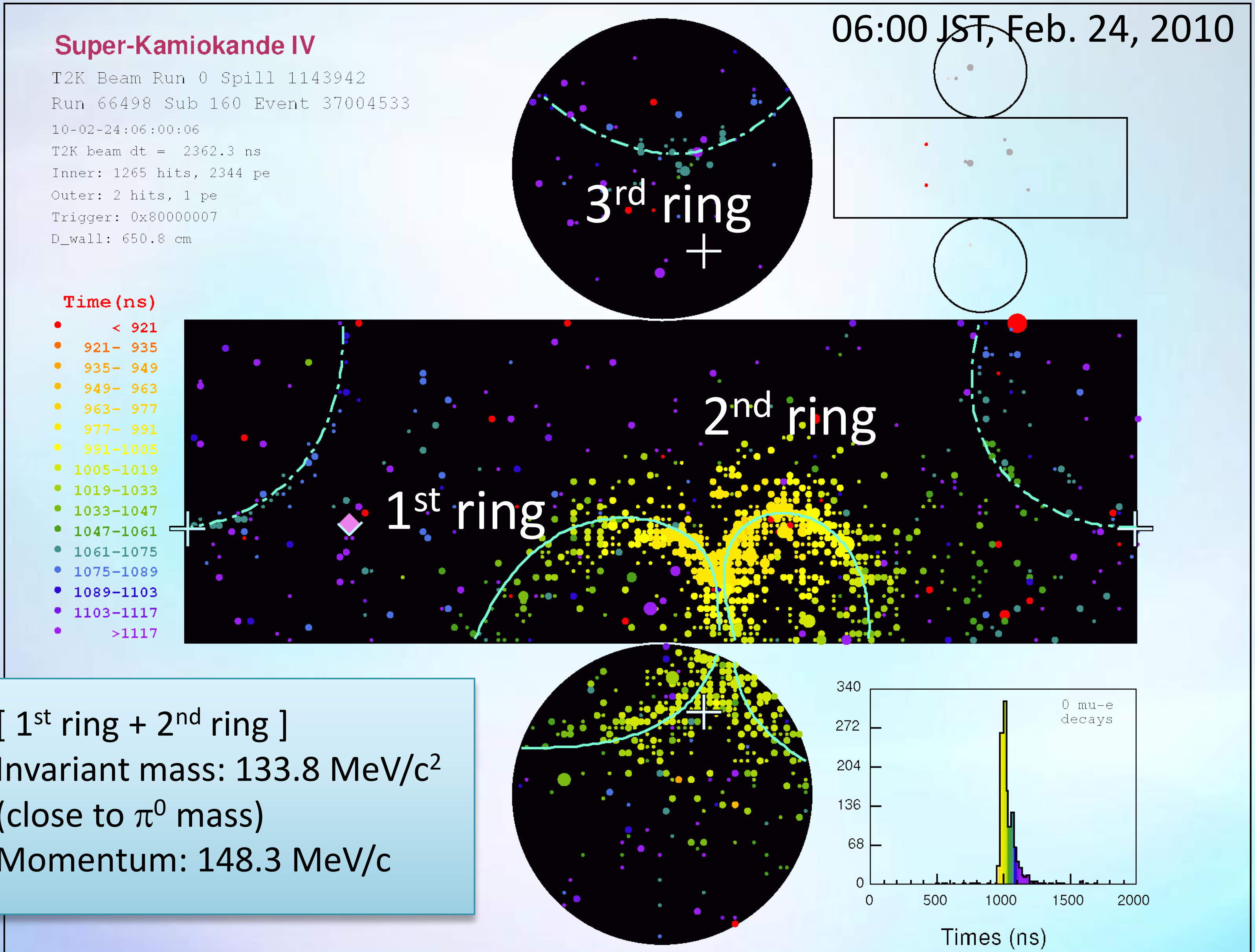


Detected the neutrino event w/ the full setup.



Calibration of the detectors is ongoing.

T2K 1st neutrino event in Super-K



[1st ring + 2nd ring]
Invariant mass: 133.8 MeV/c^2
(close to π^0 mass)
Momentum: 148.3 MeV/c

Summary

- Neutrino oscillation is physics beyond the Std. Model.
- The T2K long baseline neutrino oscillation experiment started searching for the ν_e appearance.
  - The beam commissioning succeeded; all the components are working as expected.
  - The beam direction can be measured precisely by the muon monitor.
  - The beam line parameters have been fixed.
  - 100 kW x 10^7 sec data will be accumulated in 2010.
  - First physics result is expected around summer 2010.

Supplement

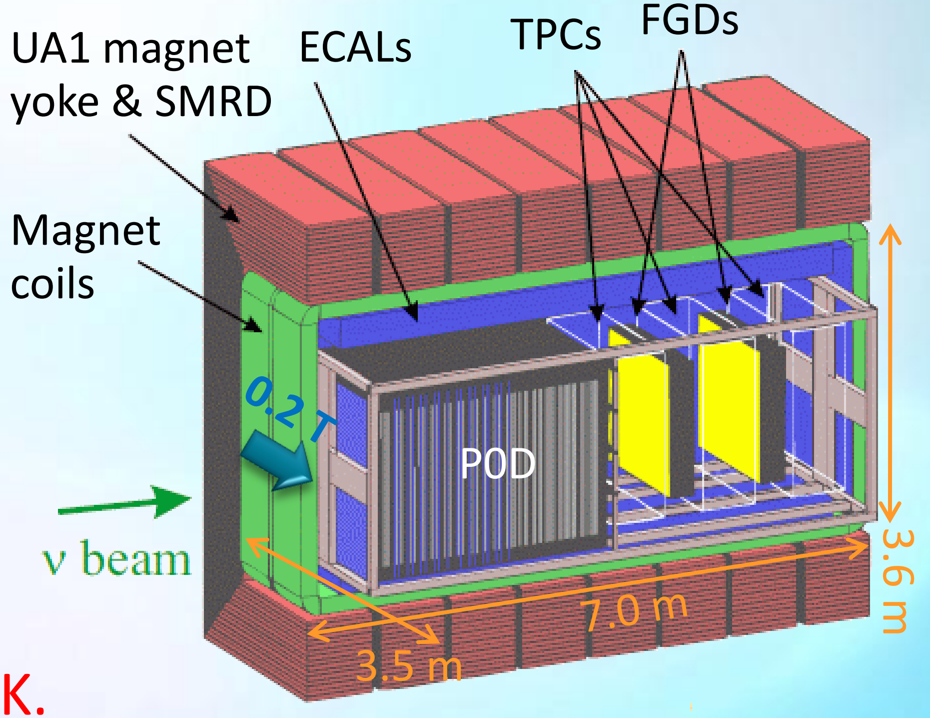
J-PARC


Jul. 16, 2009
Super-K
ND280
Muon monitor
Beam dump
LINAC
RCS
TS
Main Ring

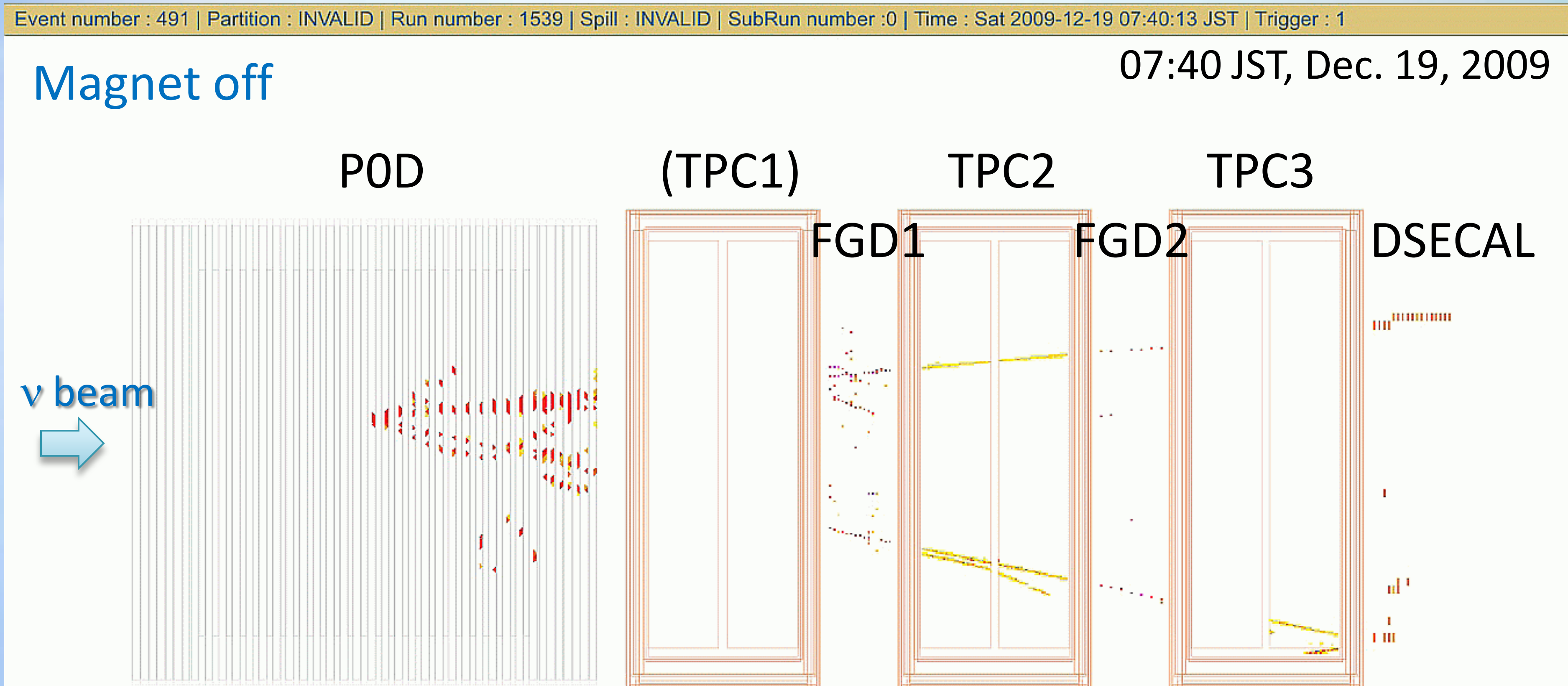
Near detectors (ND280)

- Measure ν beam energy spectrum, flux, flavor and interaction x-sec before the ν oscillation.
  - **Fine Grain Detectors (FGDs)** measure neutrino vertices.
    - Scintillator bars (FGD1), scintillator bars + water (FGD2)
  - **TPCs** measure p_μ to reconstruct E_ν spectrum and dE/dx for particle ID.
    - MicroMegas w/ Ar/iC_4H_{10}/CF_4 (95/2/3) gas mixture
  - **Side Muon Range Detector (SMRD)** measures the range of μ.
    - Scintillator planes btw the yokes
  - **π^0 detector (P0D)** measures the rate of NC-π^0 production.
    - Scintillator bars + lead foil/water
  - **ECALs** measure electrons from FGD and γ-rays from π^0.
    - Scintillator bars + lead foil

⇨ Extrapolate the ν energy spectrum and flux to Super-K.



1st neutrino event in ND280

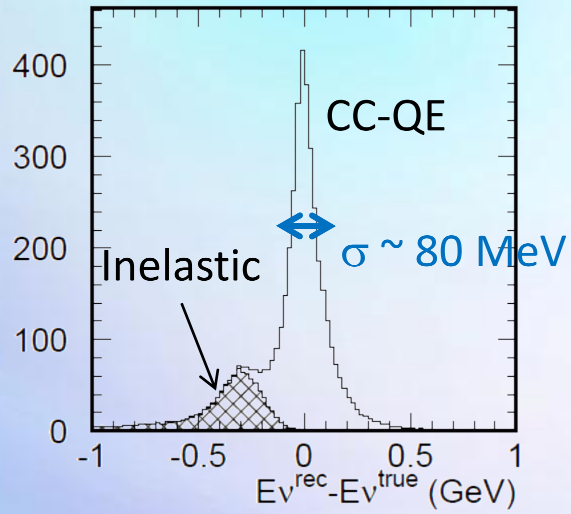


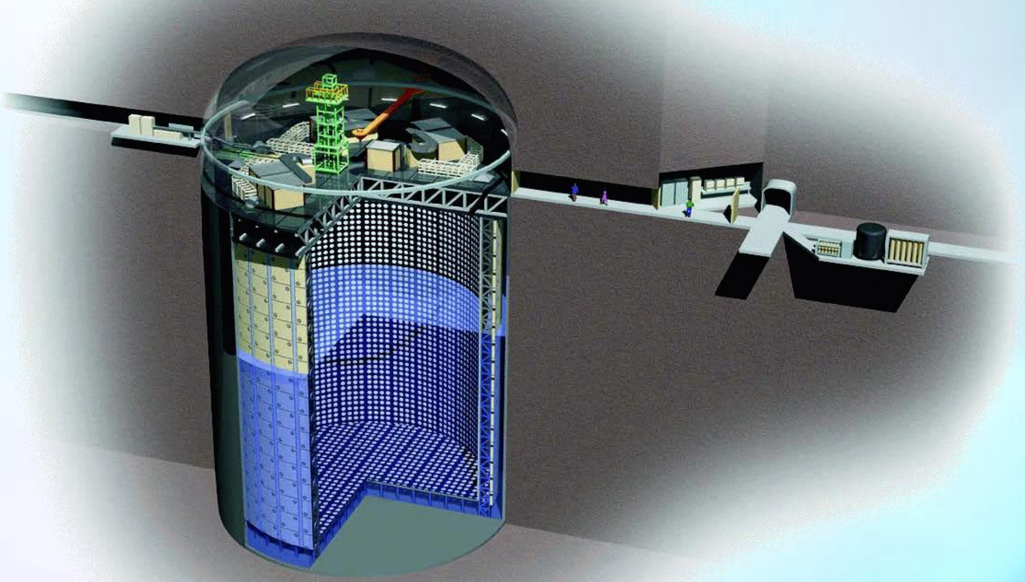
TPC1 was not taking data

Interaction inside P0D, with tracks through all central detectors.

Super-KAMIOKANDE detector

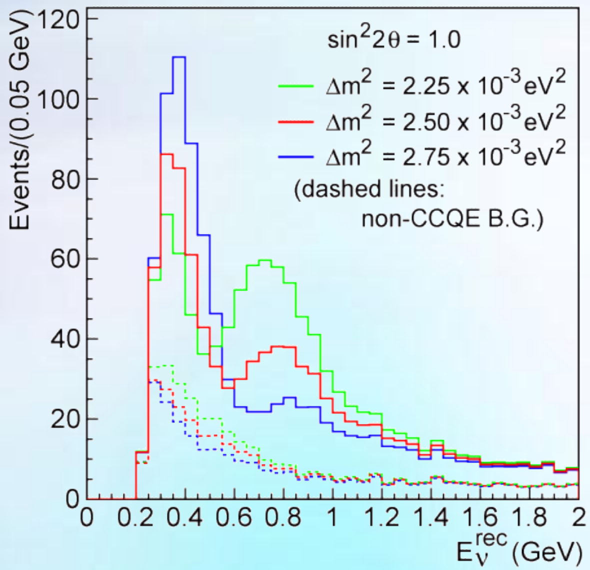
- 50-kton water Cherenkov detector (fiducial volume: 22.5 kt).
- ~11,000 20-inch PMTs (inner detector).
- Good *e*-like (shower ring) / μ-like separation. CC-QE mis-PID probability: ~1%
- σ_E ~ 80 MeV (~10%) limited by Fermi motion, δE_{scale} ~ 2%.
- New electronics & DAQ has been stably running since summer 2008.
  → Improvement of decay-*e* tagging efficiency.
- Real-time transfer of T2K beam spill information.
  → Trigger of T2K event.

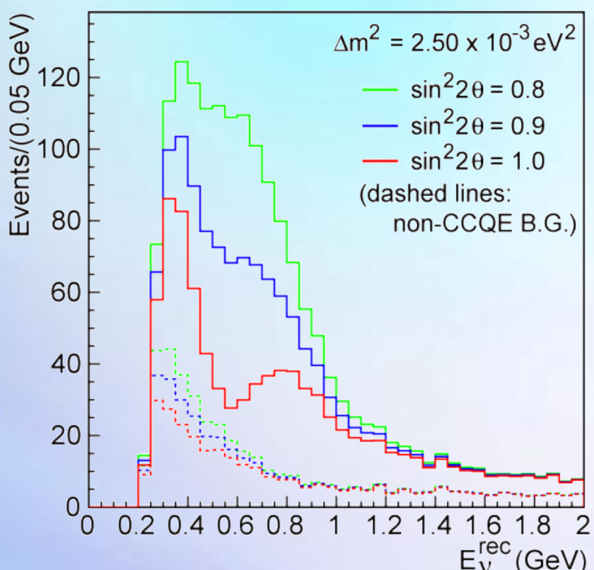




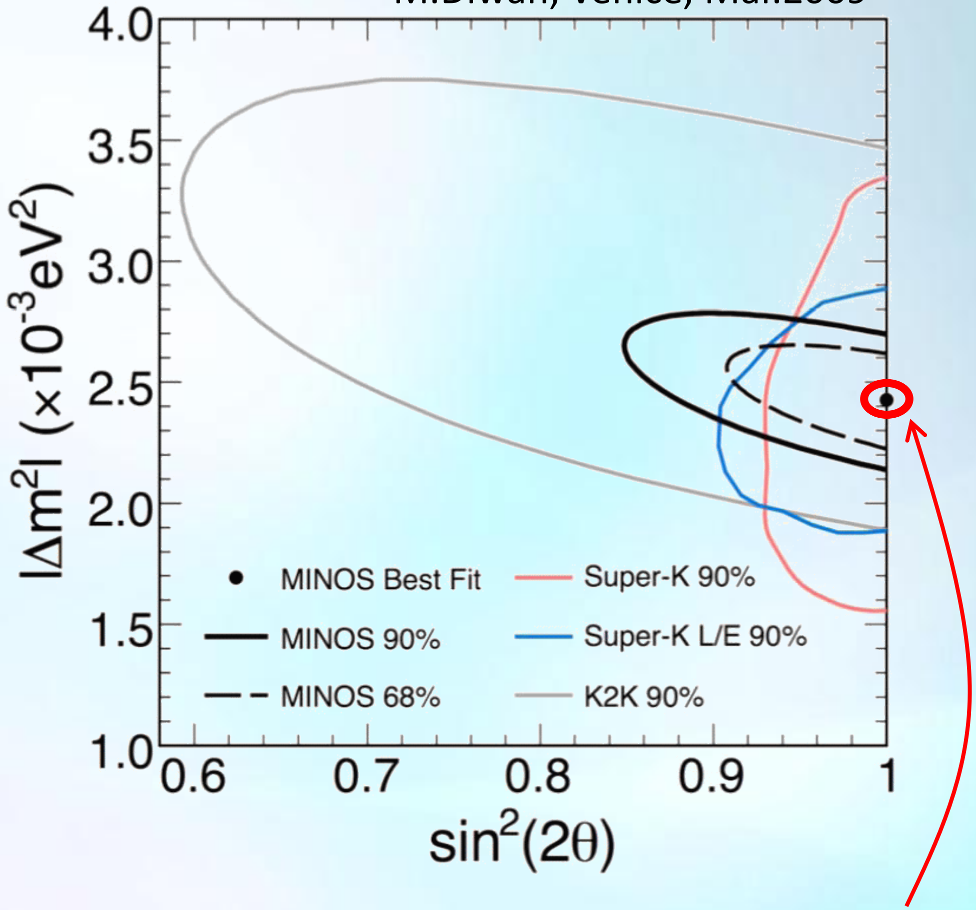
Sensitivity to Δm_{23} and θ_{23}

30 GeV, 8.3 x 10^{21} POT





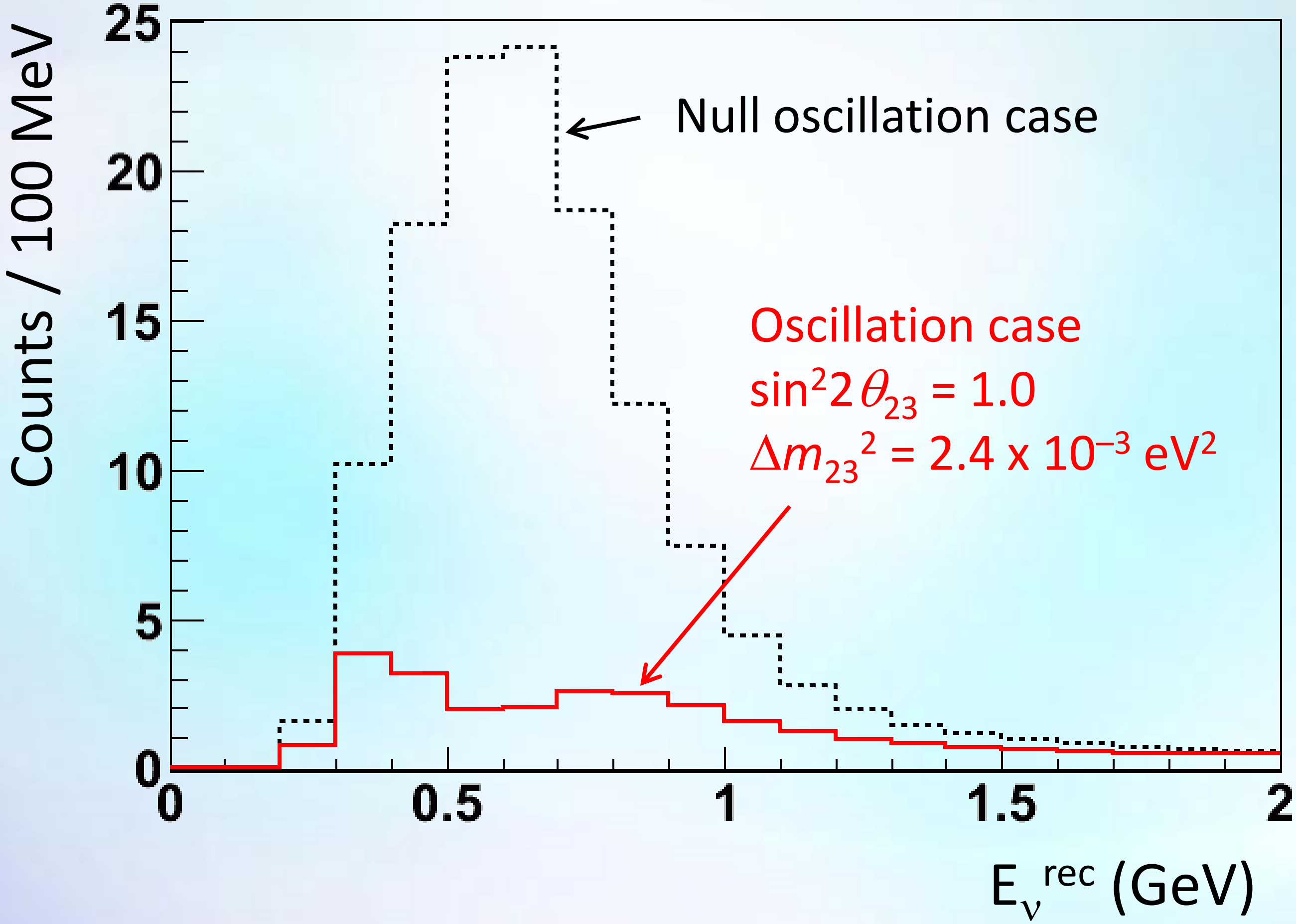
M.Diwan, Venice, Mar.2009



$\delta(\sin^2 2\theta_{23}) \approx 0.01$, $\delta(\Delta m_{23}{}^2) < 10^{-4}\ \mathrm{eV}^2$

Sensitivity to Δm_{23} and θ_{23}

100 kW x 1 x 10^7 sec

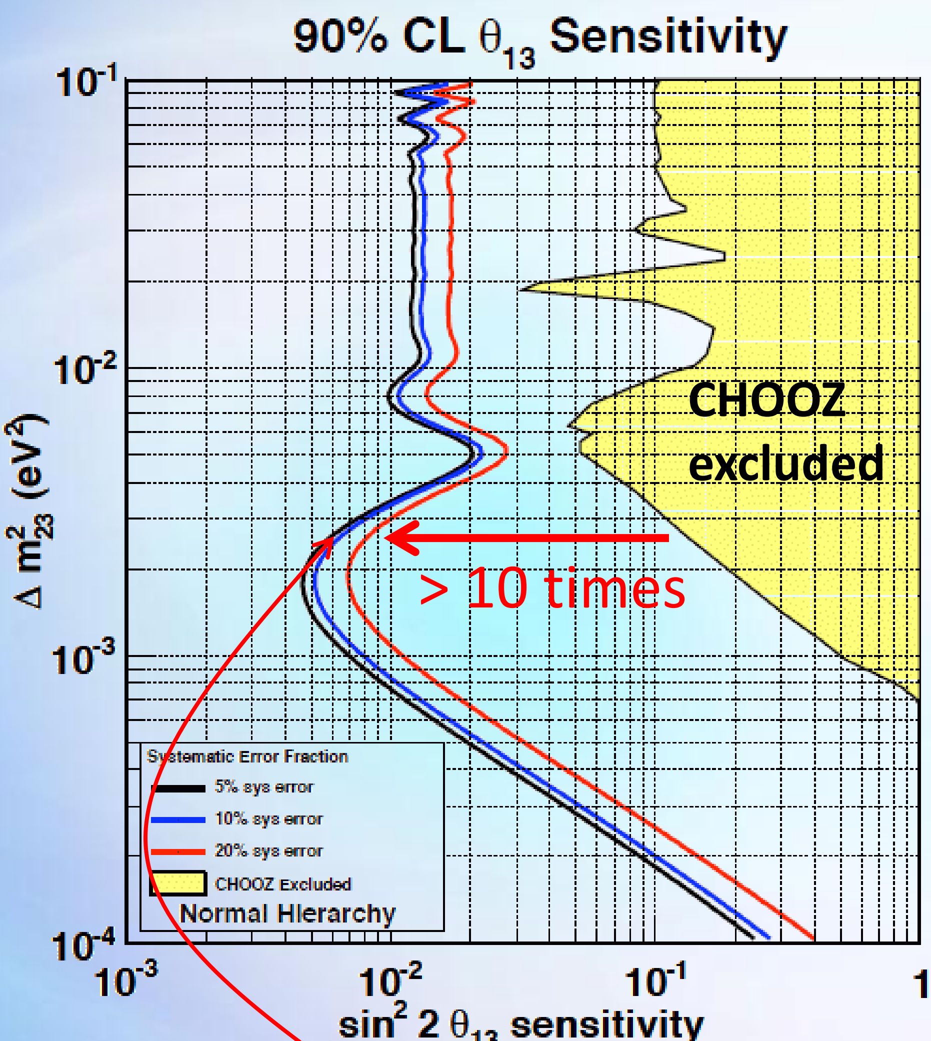


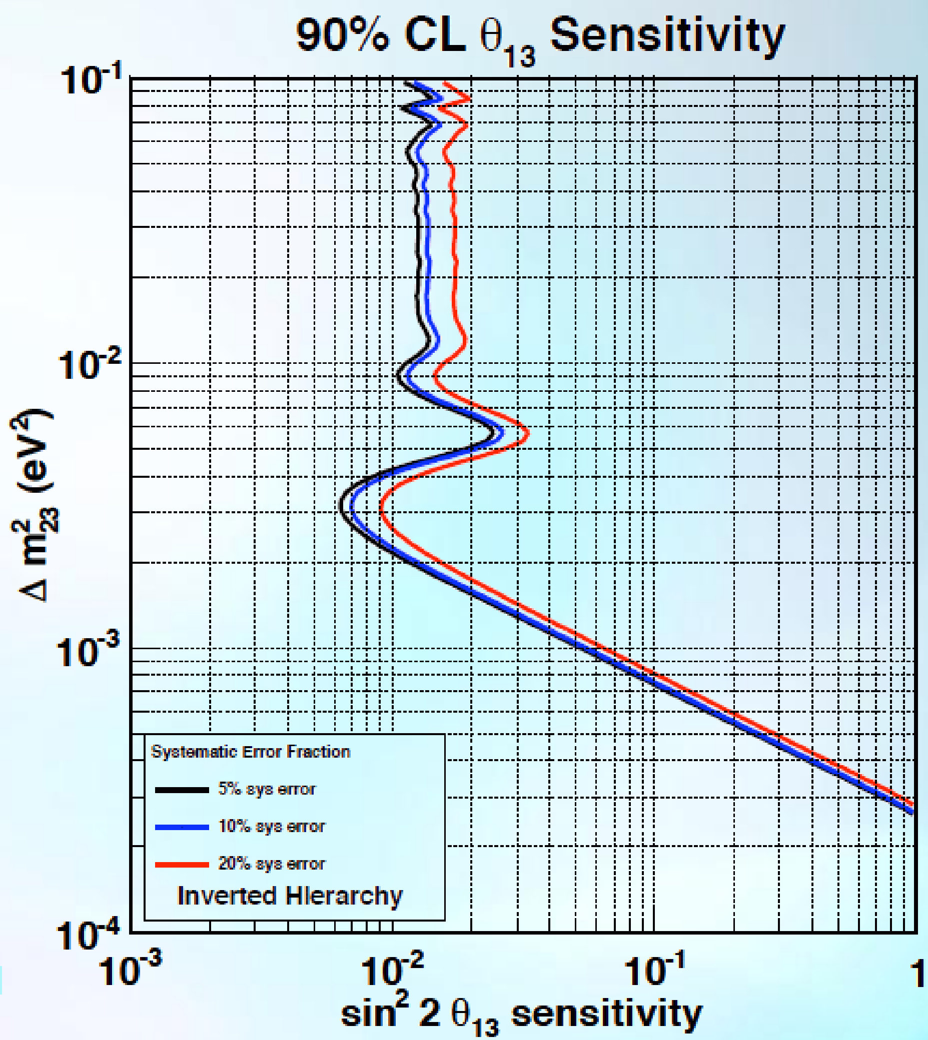
→ $\delta(\sin^2 2\theta_{23}) \approx 0.1$, $\delta(\Delta m_{23}{}^2) \approx 4 \times 10^{-4}$ eV^2 (90% CL)

(Statistical error only)

T2K sensitivity to θ_{13}

30 GeV, 8.3 x 10^{21} POT
$\delta_{CP} = 0$

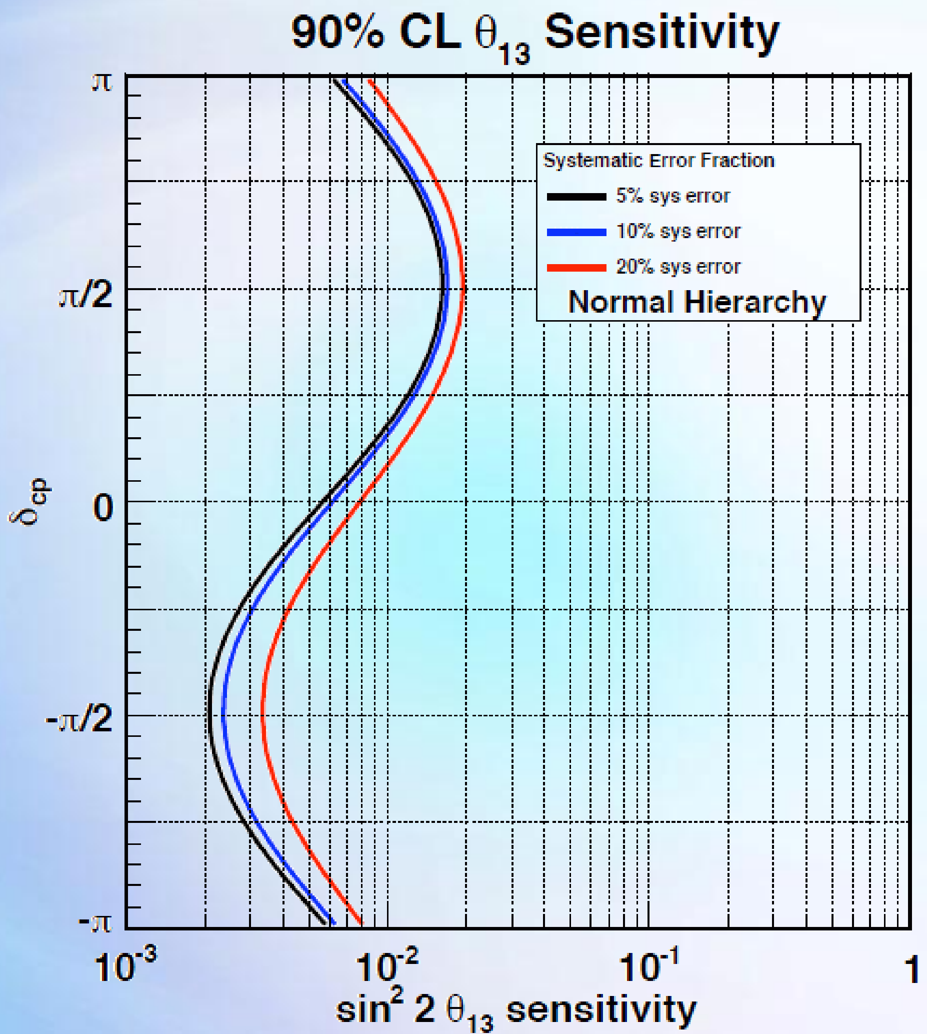


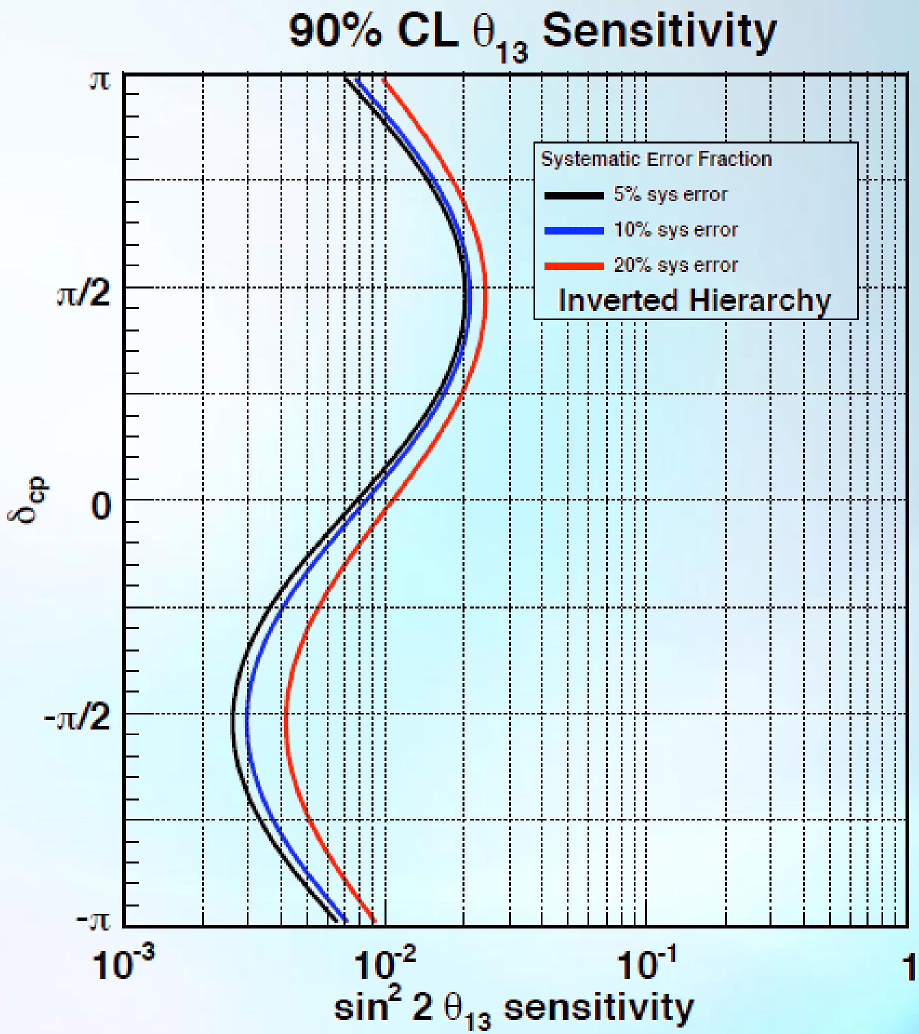


0.0060 @ $\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV^2
(for a 10% sys. error)

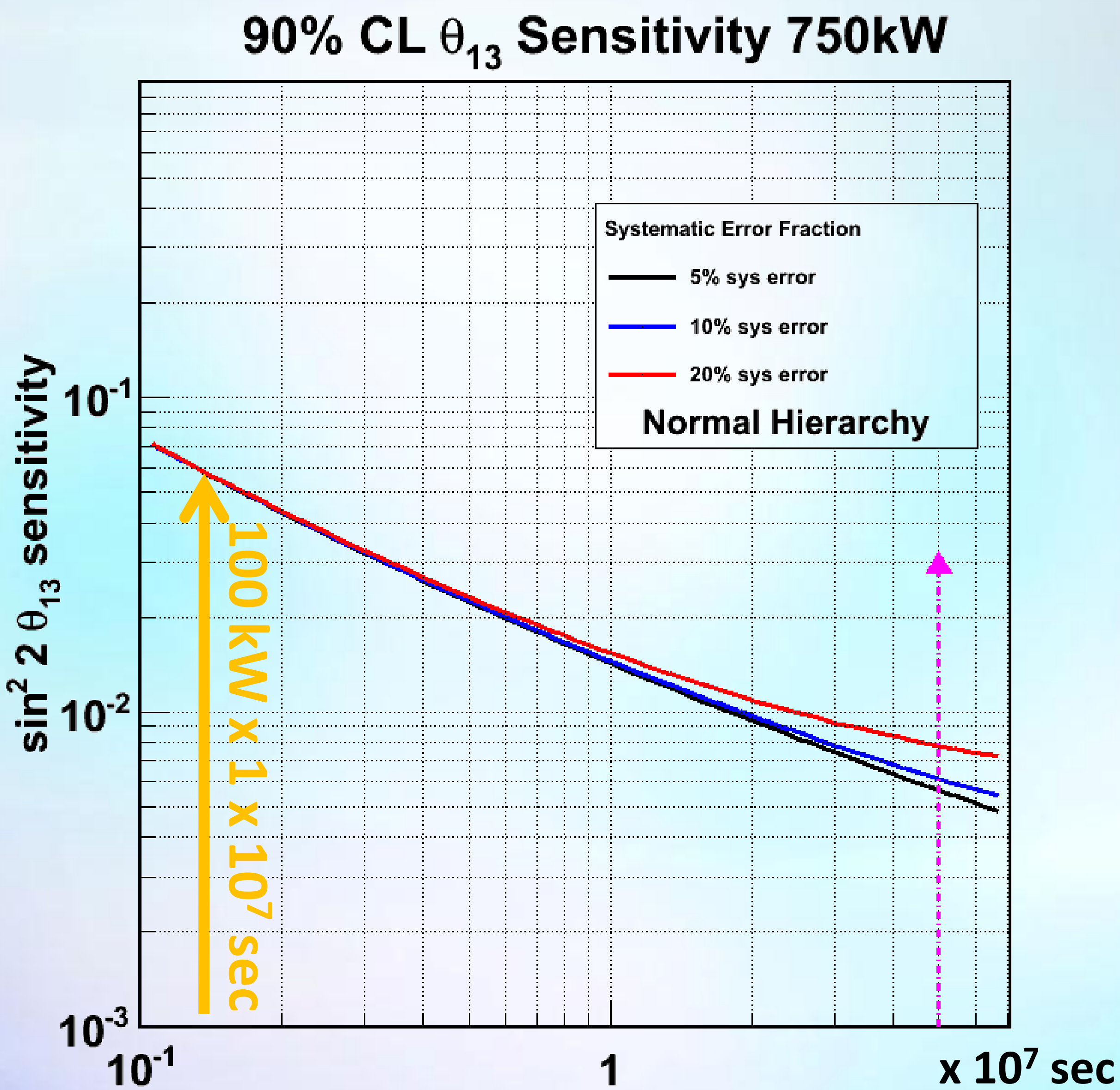
T2K sensitivity to θ_{13}

30 GeV, 8.3 x 10^{21} POT
$\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV^2





T2K sensitivity to θ_{13}



Seek for the neutrino CP-violation

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 + \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

$$T_1 = \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$ Atmospheric

$$T_2 = \underbrace{\sin\delta}_{\text{CPV}} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$ CP-violating

Interference

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$ CP-conserving

$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$ Solar

$$\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2 \sim 1/30 \qquad \Delta \equiv \Delta m_{31}^2 L / 4E \qquad x \equiv 2\sqrt{2} G_F N_e E / \Delta m_{31}^2$$

G_F: Fermi coupling constant N_e: electron number density

For $\bar{\nu}_\mu \to \bar{\nu}_e$, $\delta \to -\delta$ and $x \to -x$. $P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq P(\nu_\mu \to \nu_e)$.