# The T2K Neutrino Oscillation Experiment

## And Possible Future Projects

Nicholas Hastings

Heavy Quarks and Leptons 2008

# Outline

Introduction

T2K

Possible Future Projects

Summary

# Neutrino oscillations observed

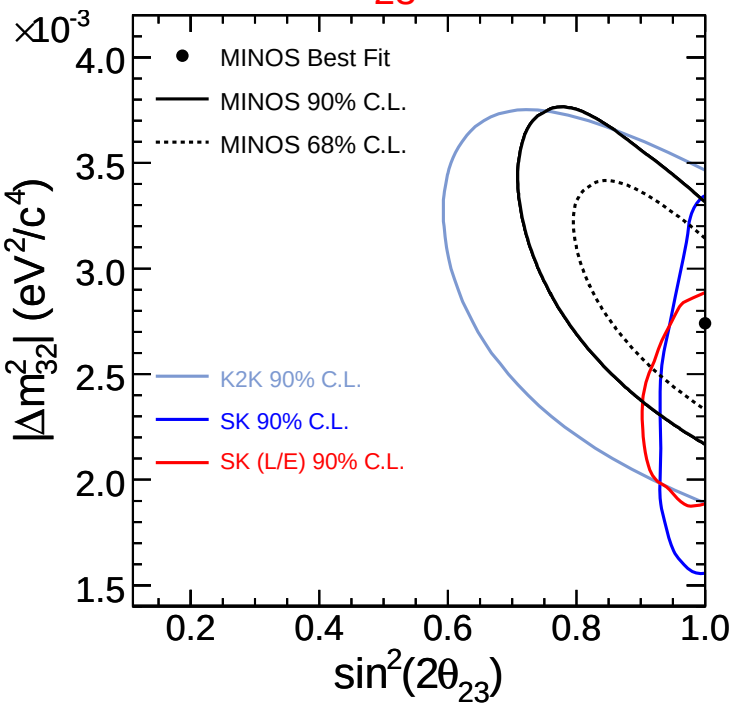
- Neutrino disappearance - oscillations confirmed
- Neutrinos have non-zero mass

## Atmo's & Long-baseline

$\nu_\mu$ disappearance

$|\Delta m^2_{23}| = (2.2\text{–}2.6) \times 10^{-3}\ eV^2$

$\sin^2 2\theta_{23} > 0.9$

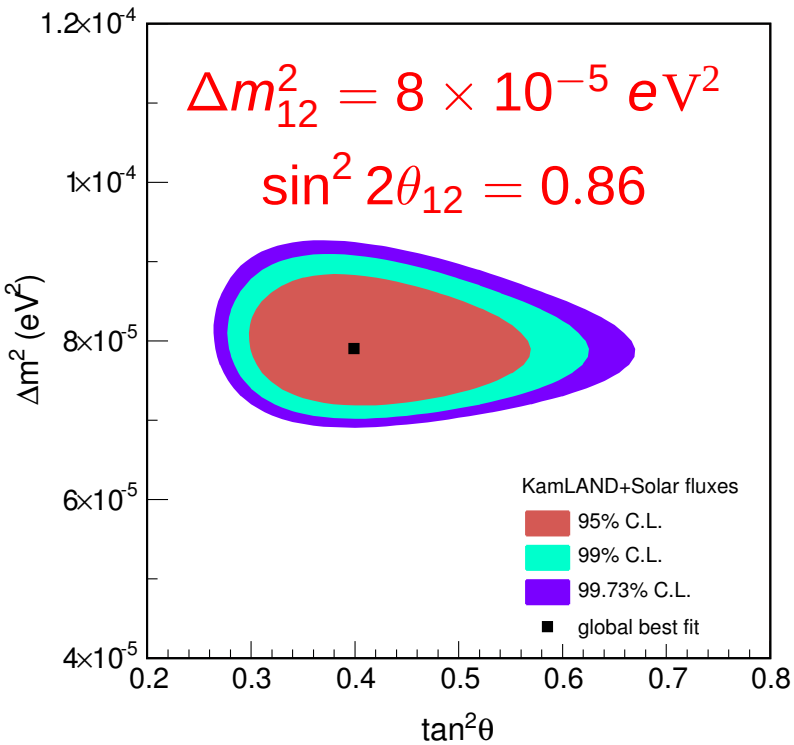



## KamLAND & Solar

$\nu_e$ disappearance

$\Delta m^2_{12} = 8 \times 10^{-5}\ eV^2$

$\sin^2 2\theta_{12} = 0.86$



# The Parameters

$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}_{\text{Flavour}} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmo's \& Long BL}} \overbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}^{\text{Unknown}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{KamLAND \& Solar}} \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}_{\text{Mass}}$$

where $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$

- Is $\sin^2 2\theta_{23}$ maximal?
- $\theta_{13}$ known to be small
- CHOOZ 90%CL $\sin^2 2\theta_{13} < 0.12$–$0.20$
- No information on $\delta$

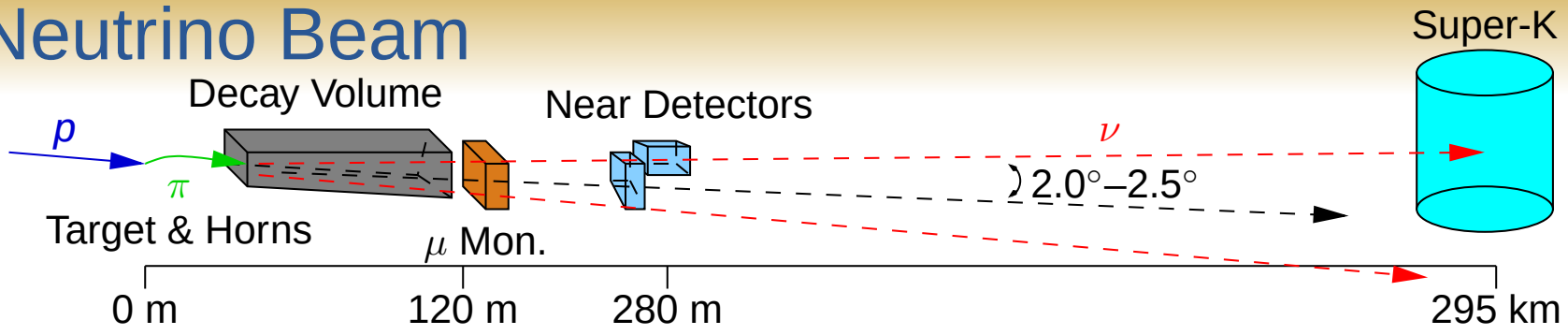
## T2K Goals

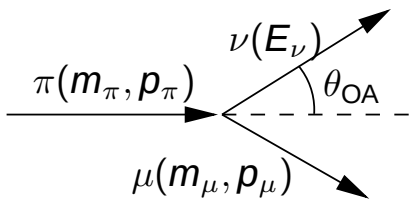
- Refine $\nu_\mu$ disappearance
  - $\Rightarrow$ Precision measurement of $\sin^2 2\theta_{23}$
- Discover $\nu_\mu \rightarrow \nu_e$
  - $\Rightarrow$ Measurement$^\star$ of $\sin^2 2\theta_{13}$

# T2K

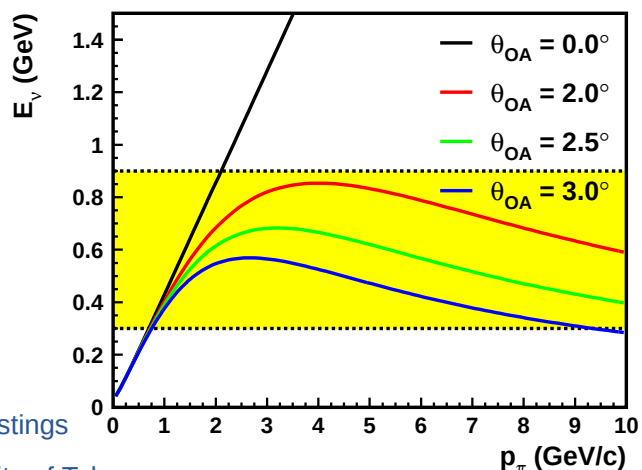
- Next generation long-baseline neutrino oscillation experiment
- T2K: 5 years $\times$ 0.75 MW, Super–K ($\sim$ K2K $\times$100)
- Future: Upgraded beam and detector

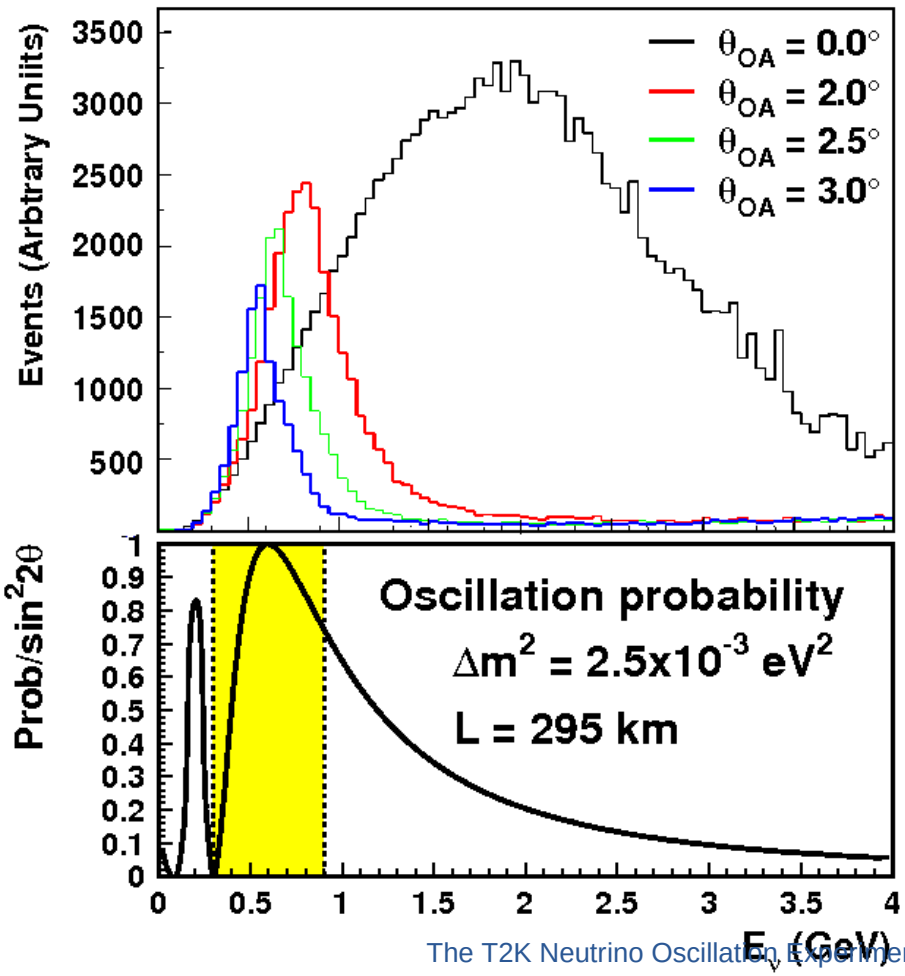
# Neutrino Beam



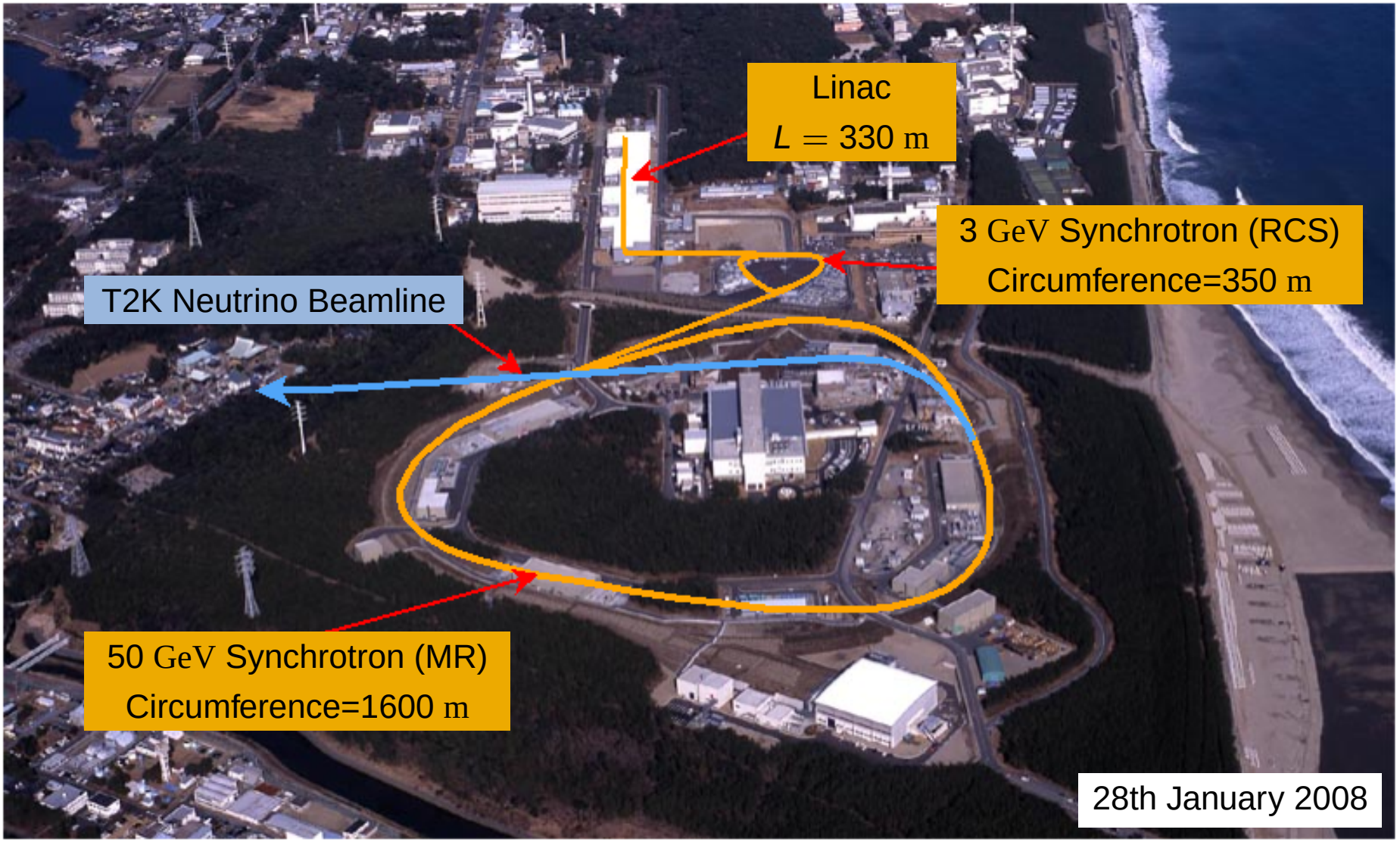




$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{OA})}$$

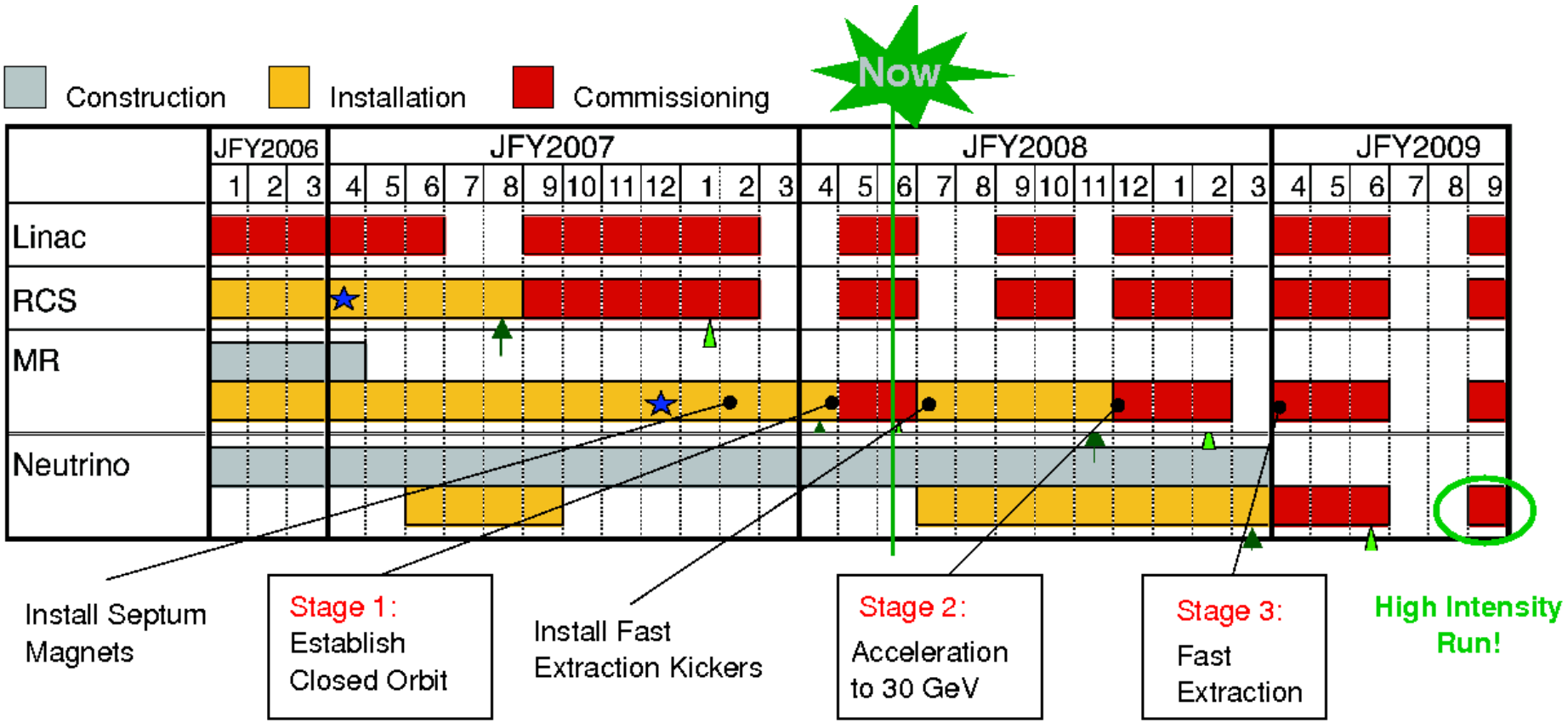


# Tokai site

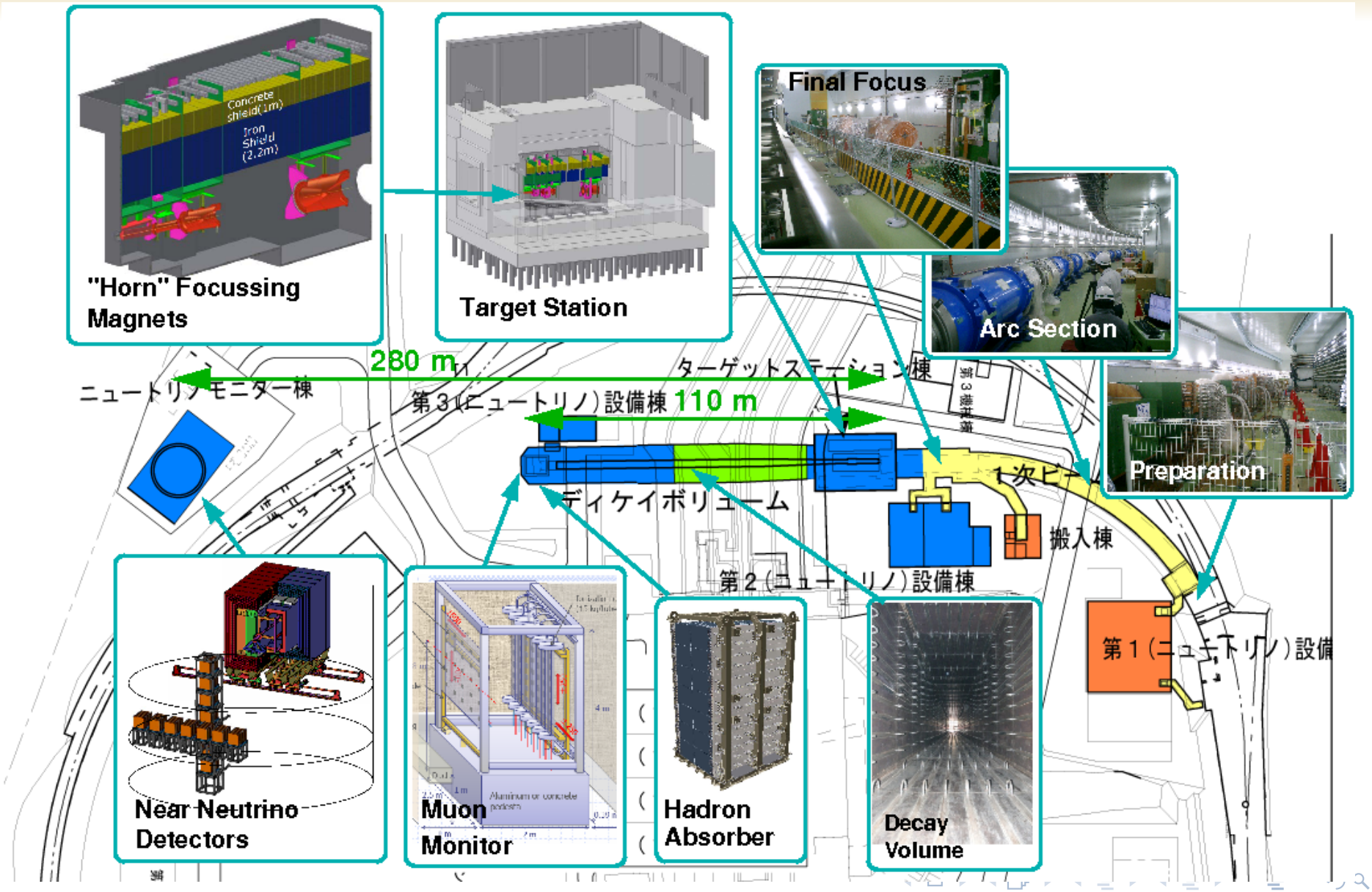

Linac
$L = 330$ m
3 GeV Synchrotron (RCS)
Circumference=350 m
T2K Neutrino Beamline
50 GeV Synchrotron (MR)
Circumference=1600 m
28th January 2008

# Commissioning Schedule

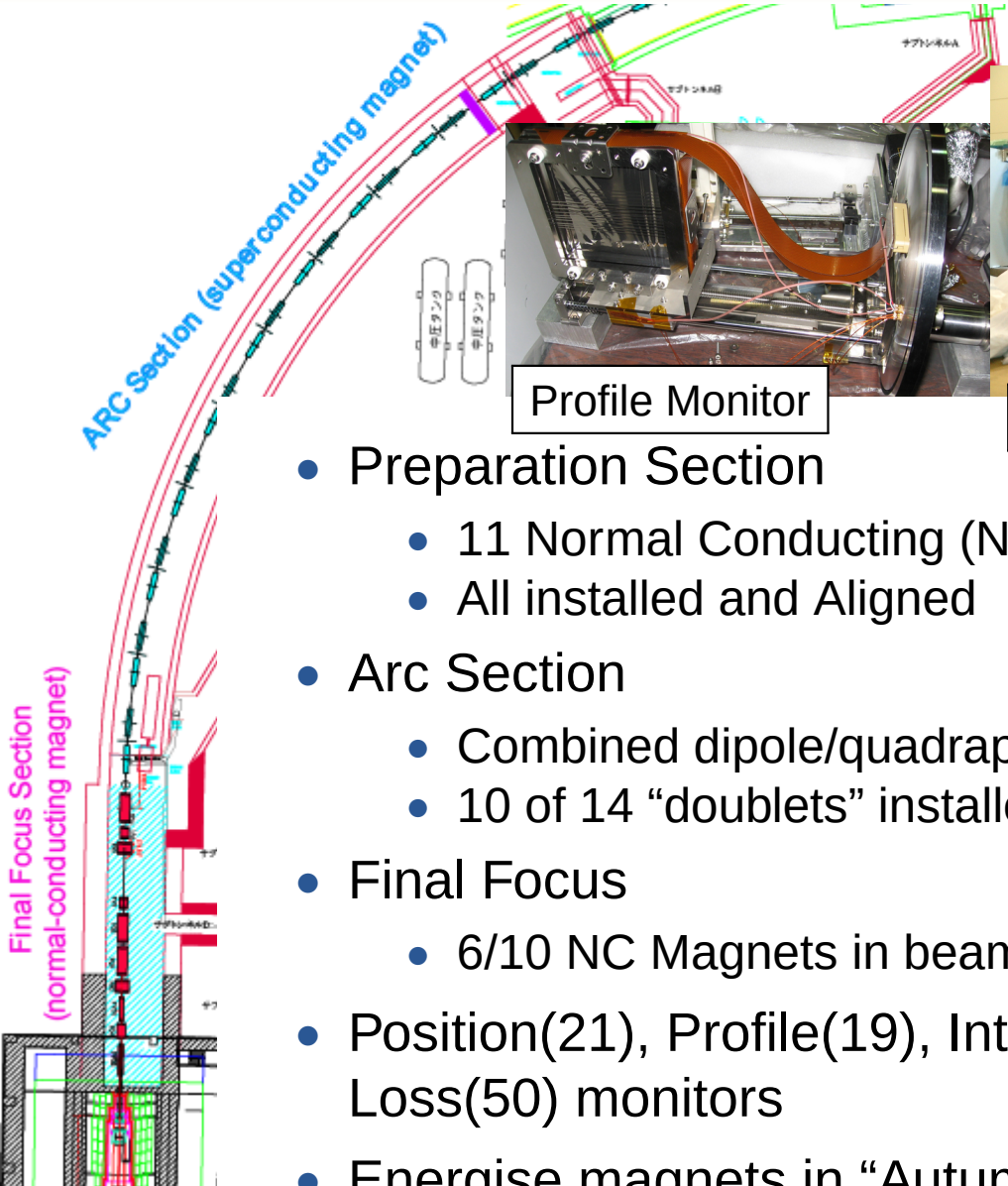



- Tune beamline with single bunch operation
- High intensity with six bunches
- 3 s repetition rate

# Beamline

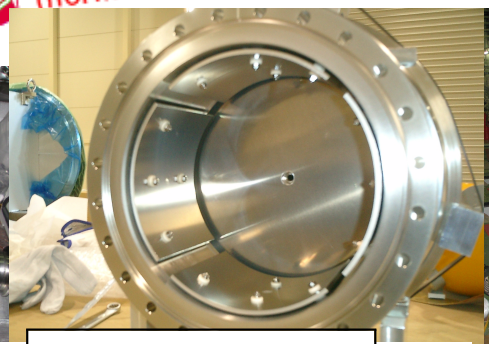

"Horn" Focussing Magnets
Concrete shield(1m)
Iron Shield (2.2m)
Target Station
Final Focus
Arc Section
Preparation
280 m
ニュートリノモニター棟
ターゲットステーション棟
第3(ニュートリノ)設備棟 110 m
ディケイボリューム
1次ビーム
搬入棟
第2(ニュートリノ)設備棟
第1(ニュートリノ)設備
Near Neutrino Detectors
Muon Monitor
Hadron Absorber
Decay Volume

# Primary Beamline






Profile Monitor

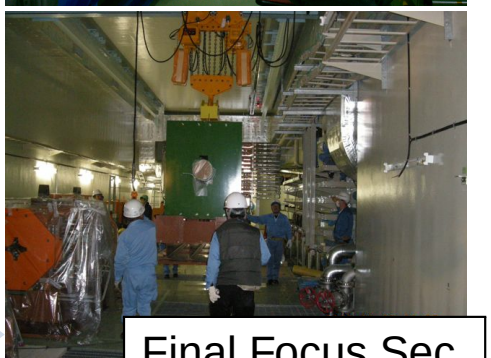


Position Monitor

Preparation Sec.

- Preparation Section
  - 11 Normal Conducting (NC) magnets
  - All installed and Aligned
- Arc Section
  - Combined dipole/quadrapole S.C. magnets
  - 10 of 14 “doublets” installed
- Final Focus
  - 6/10 NC Magnets in beamline
- Position(21), Profile(19), Intensity(5) & Loss(50) monitors
- Energise magnets in “Autumn”

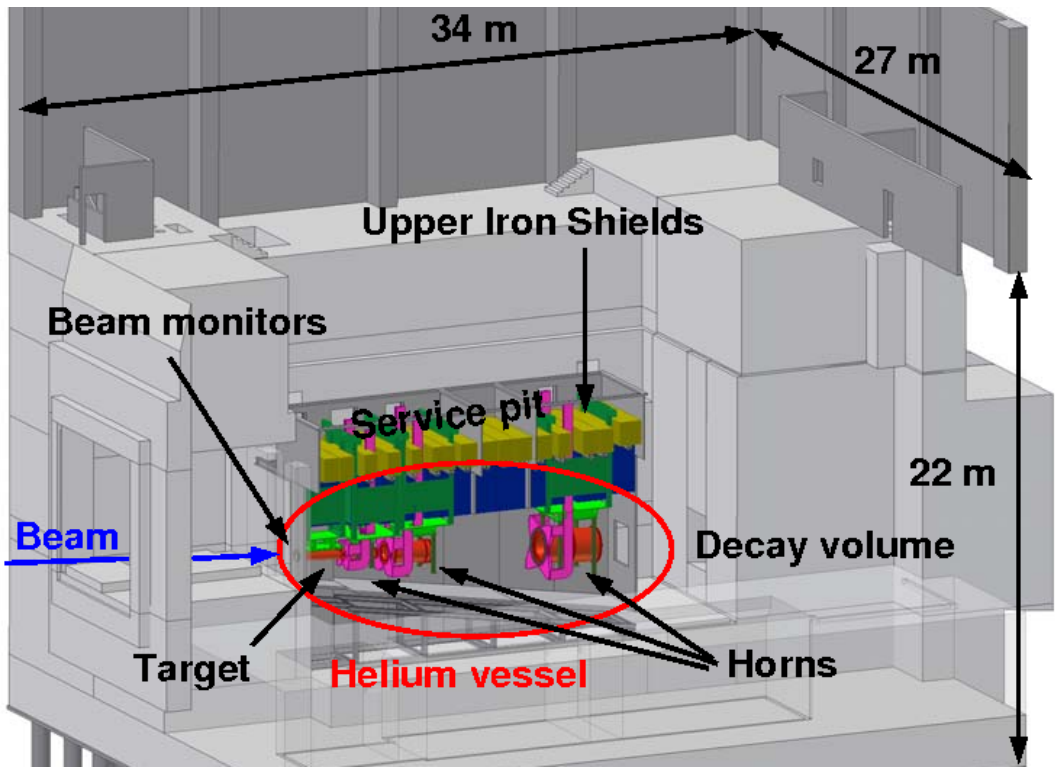
Arc Sec.

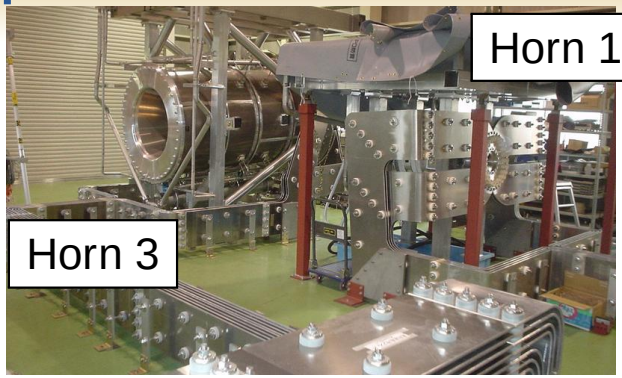


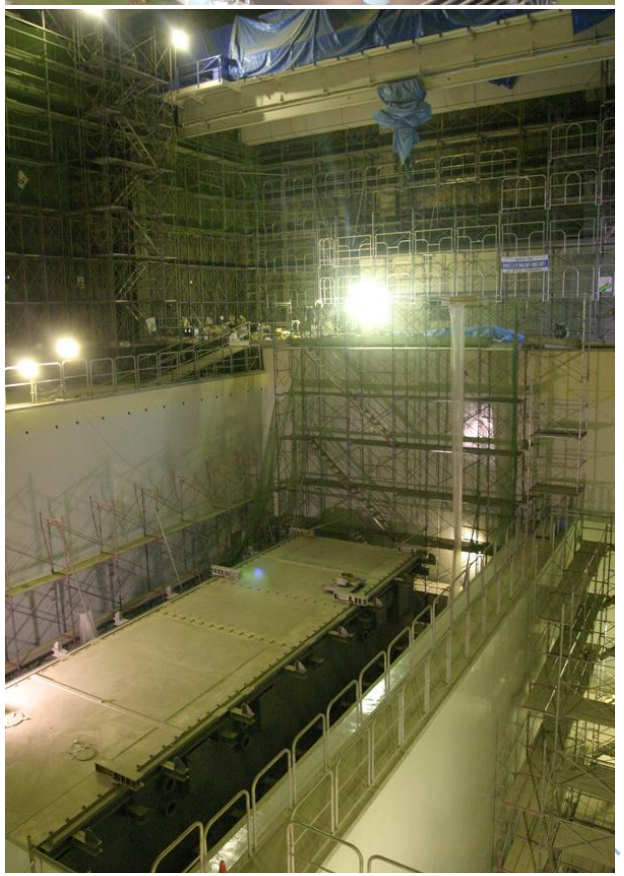
Final Focus Sec.

# Secondary Beamline - Target Station

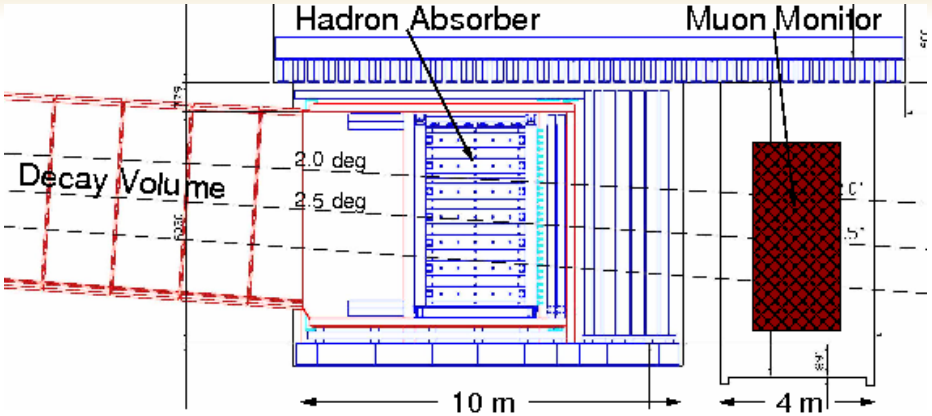
- Graphite target
- Remote target replacement
- Horns tested to 320 kA
- Remote crane for horn maintenance
- Civil construction completed this month

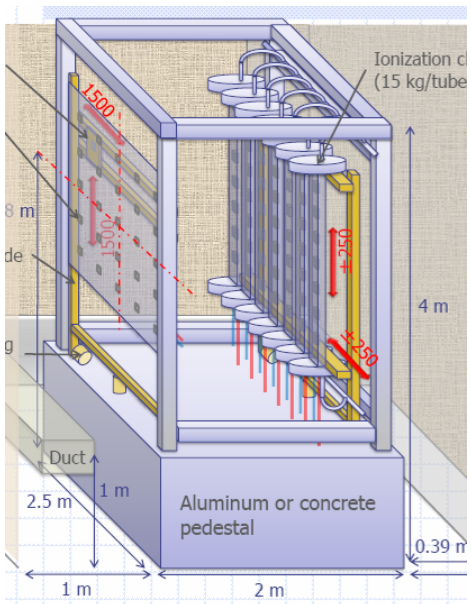


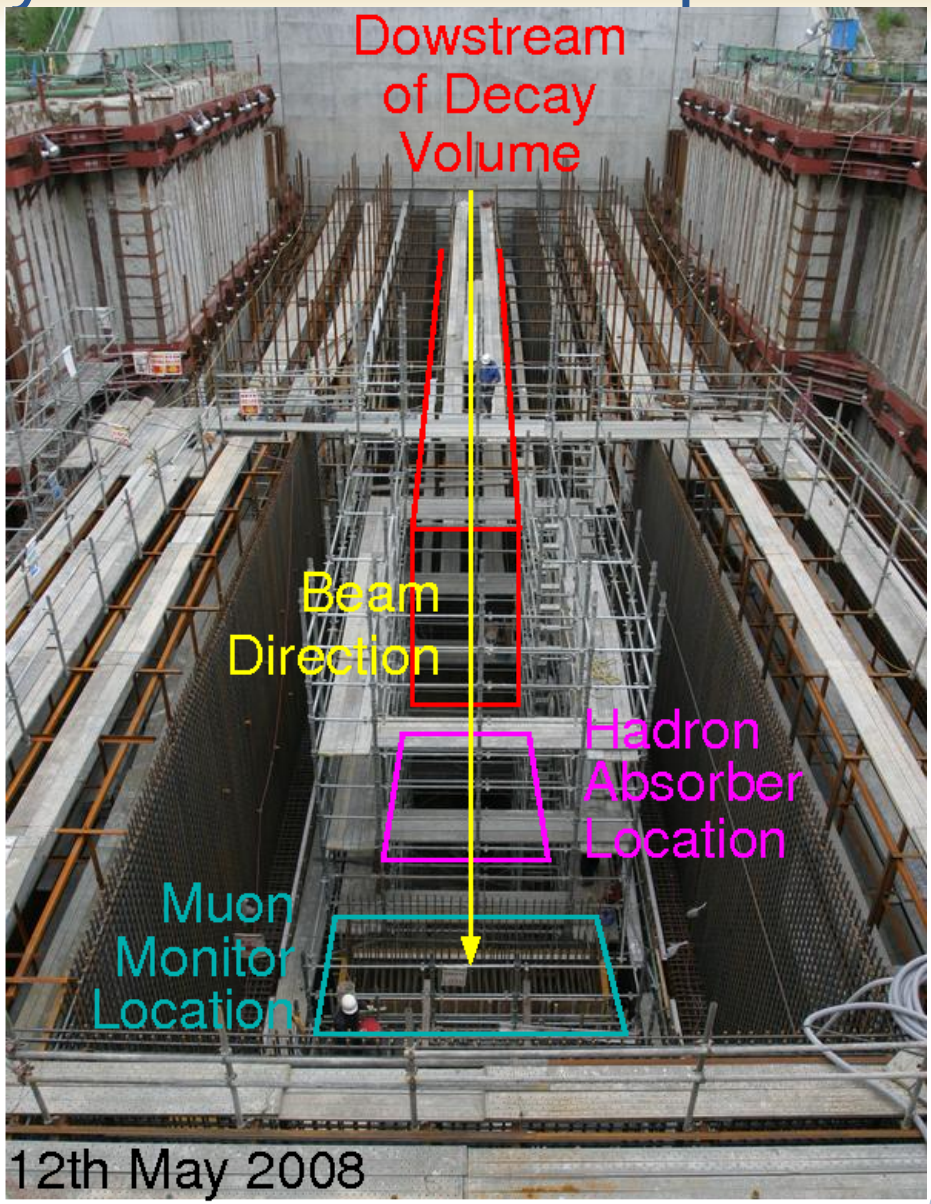



# Secondary Beamline - Decay Vol. & beam dump






## Hadron Absorber

Install in October 2008

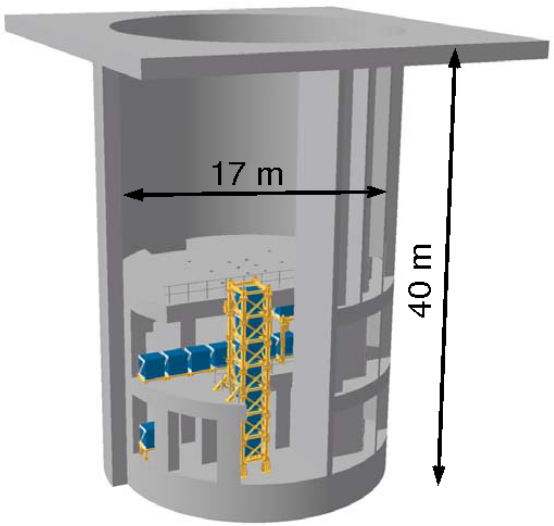
## Muon Monitor

Install by end 2008

# Near Detectors @ 280 m

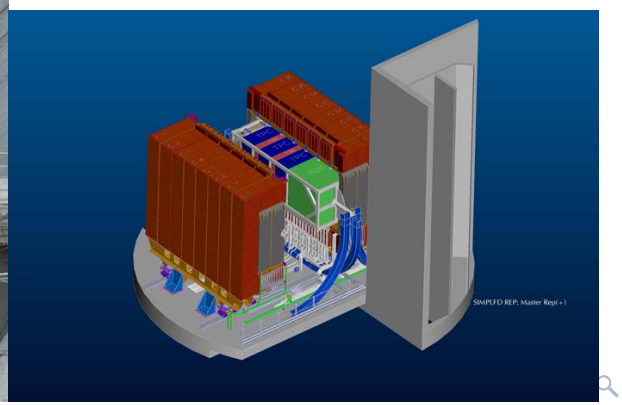
## INGRID (On-Axis)

- Iron-scintillator stacks
- 10 m $\times$ 10 m coverage
- Monitor $\nu_\mu$ profile & direction
- $\sigma_\theta = 0.18$ mrad
- Res. corresponds to 1 mm at target
- Complete by April 2009

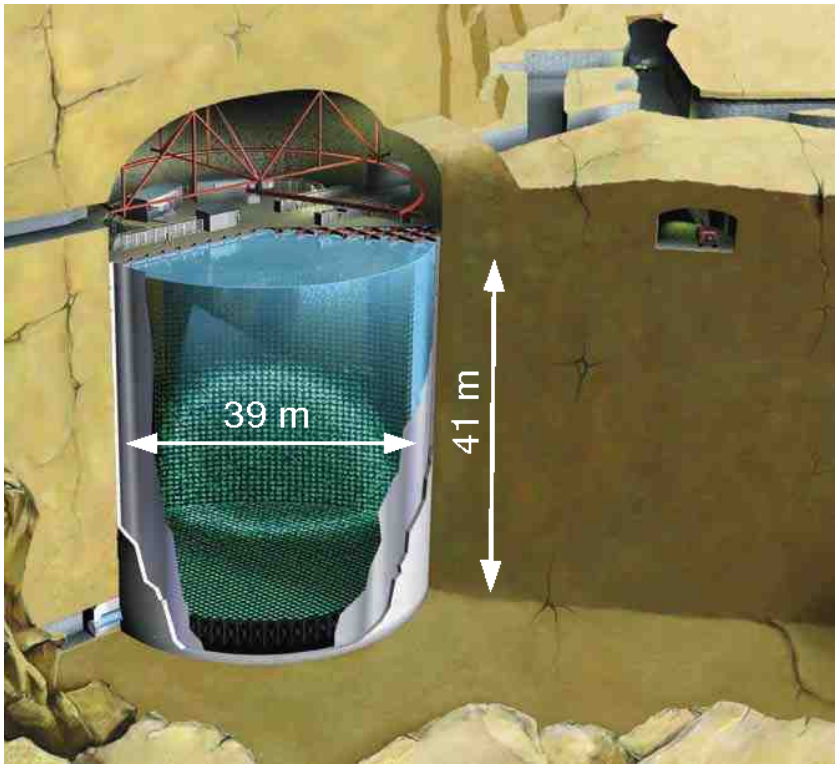


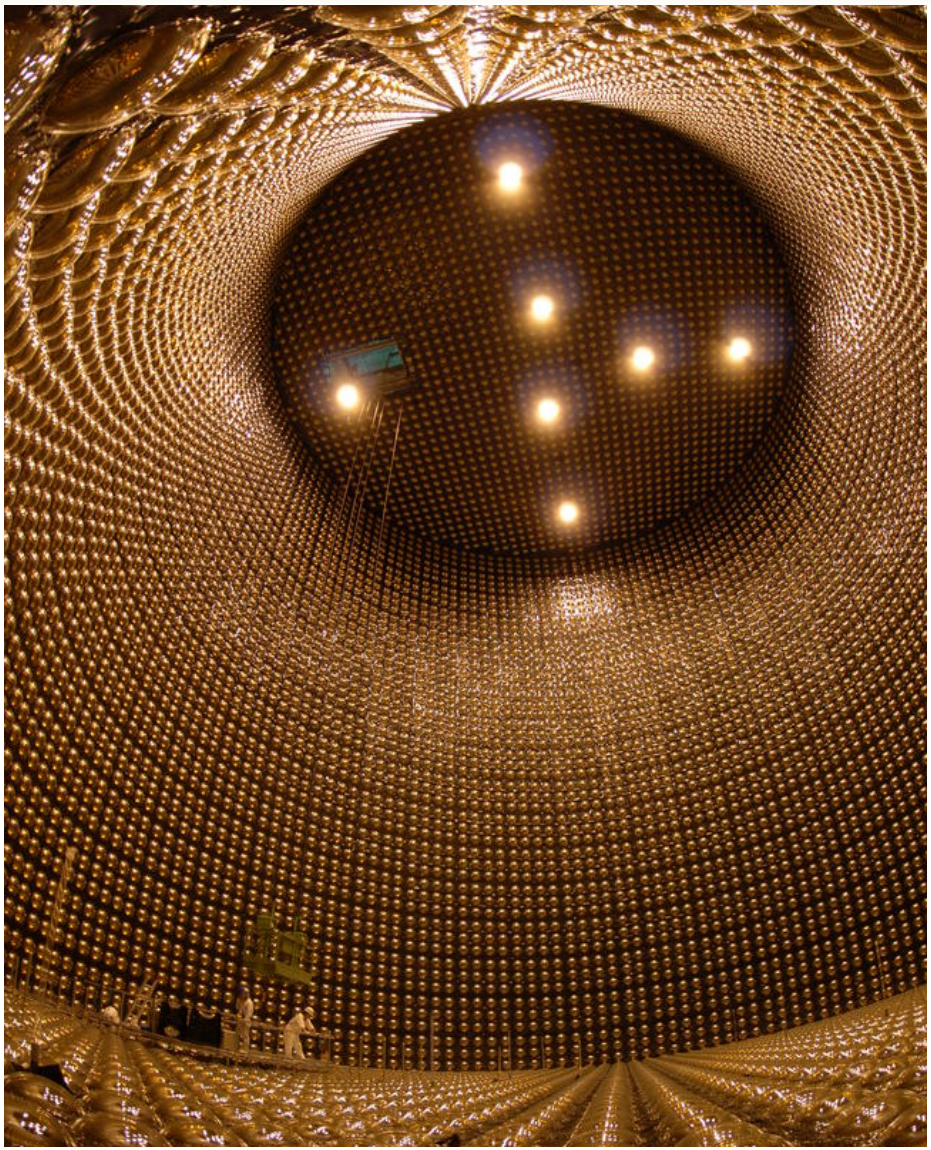
## ND280 (Off-Axis)

- Meas. $\nu$-flux in direction of SK
  - Both $\nu_\mu$ and $\nu_e$
  - Tracker for CC-QE kinem. ($E_\nu$)
- Cross sections of $\nu$ interaction
  - CC-nQE vs CC-QE: for $E_\nu$
  - NC-$\pi^0$ production (fake $\nu_e$)
- Complete by “Autumn” 2009



# Far Detector - Super-Kamiokande



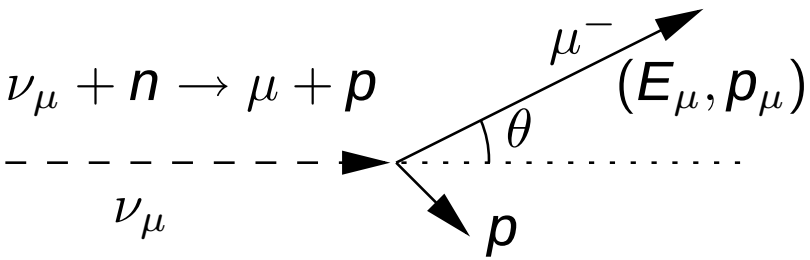



- Full PMT coverage since 2006
- 11146(inner)+1885(outer) PMTs
- Fiducial volume 22.5 kt
- New Electronics in September

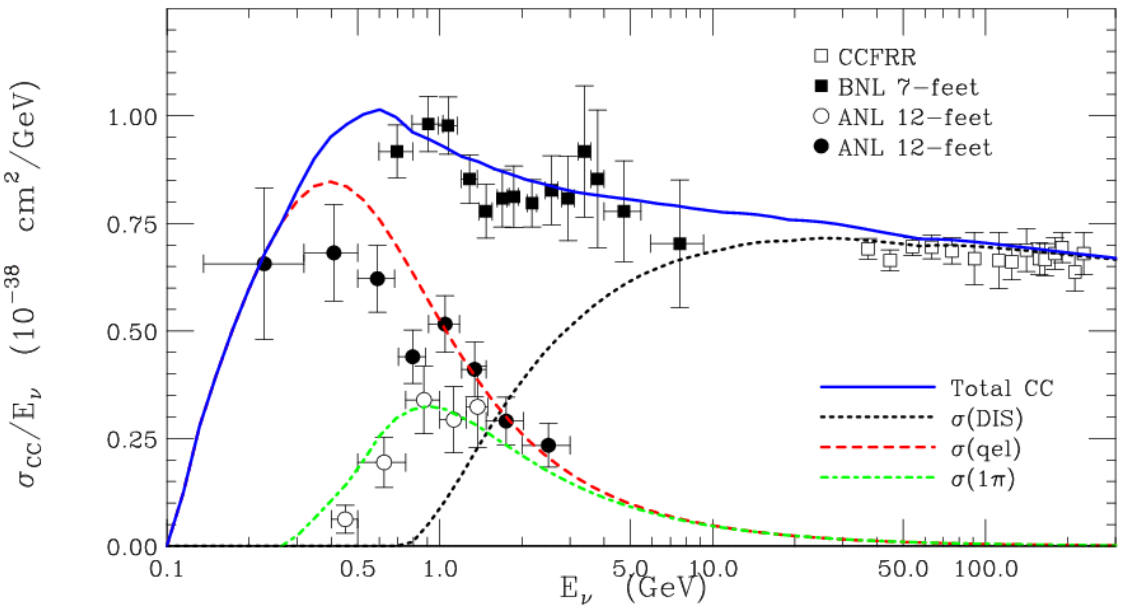
# $E_\nu$ Reconstruction

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{\mu\tau} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Charged Current Quasi-Elastic (CC-QE)




$\nu_\mu$ CC cross sections



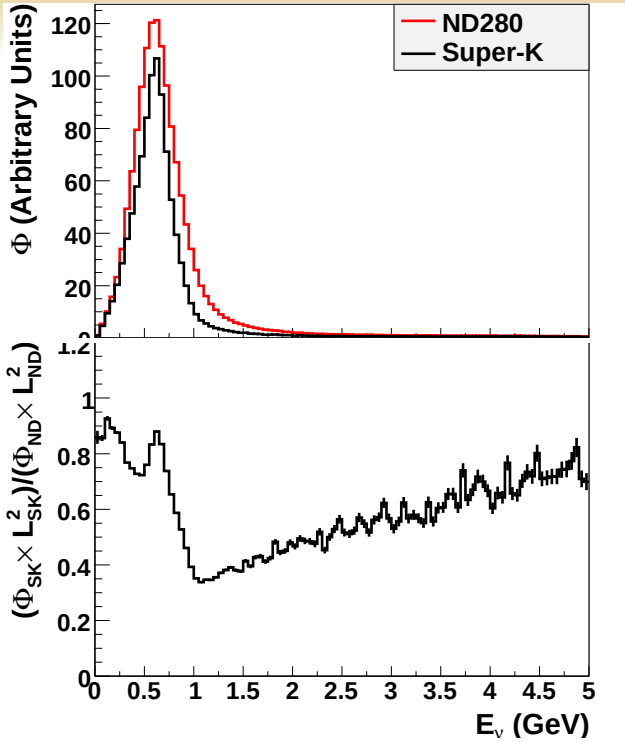

- Use energy and timing info. from PMTs
- Fit cone to PMT hits to reconstruct $(E_\mu, p_\mu)$:

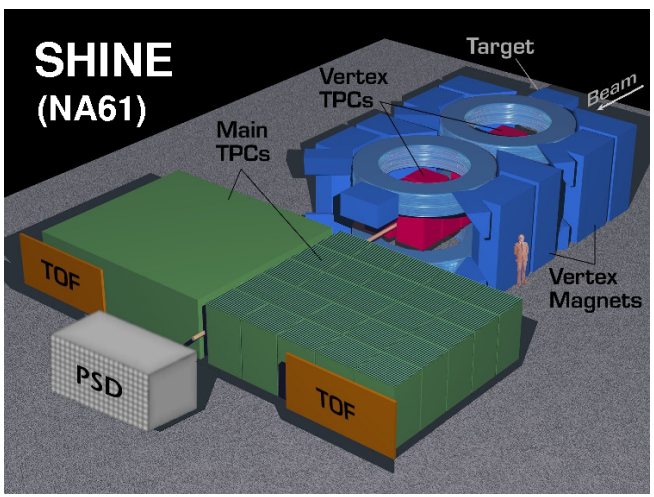
$\Rightarrow$ Calculate: $E_\nu^{\text{rec}} = \dfrac{m_n E_\mu - m_\mu^2/2}{m_n - E_\mu + p_\mu \cos\theta}$

# Extracting Results

- Look for:
  - $\nu_e$ appear.: Excess of # $e^-$
  - $\nu_\mu$ disappear.: Deficit # $\mu^-$ & dist. of $E_\nu$.
- Using:
  - $N_{ND} = \phi_{ND}\sigma_{ND}, \quad N_{SK} = \phi_{SK}\sigma_{SK}P_{osc}$
  - $\sigma_{SK,ND}, \phi_{ND}$ studied with Near Detector
  - Treat Fluxes as ratio: $R_{N/F} = \frac{\phi_{SK}}{\phi_{ND}}$
  - Need to understand hadron production...

Compare: $N_{SK}^{obs}$ to $N_{SK}^{pred} = N_{ND}^{obs} R_{N/F} \frac{\sigma_{SK}}{\sigma_{ND}}$

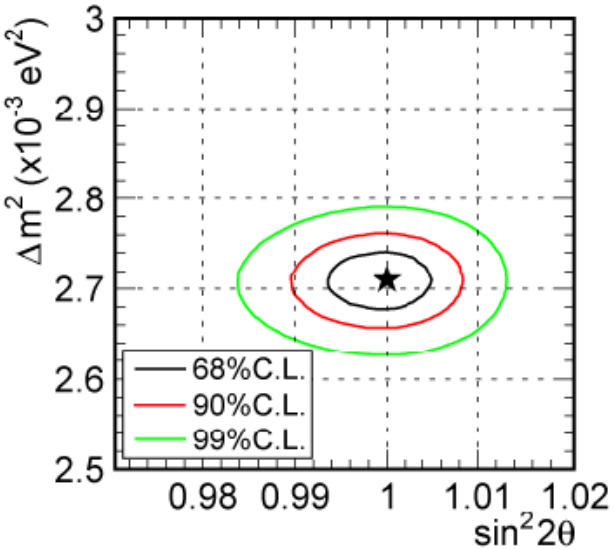


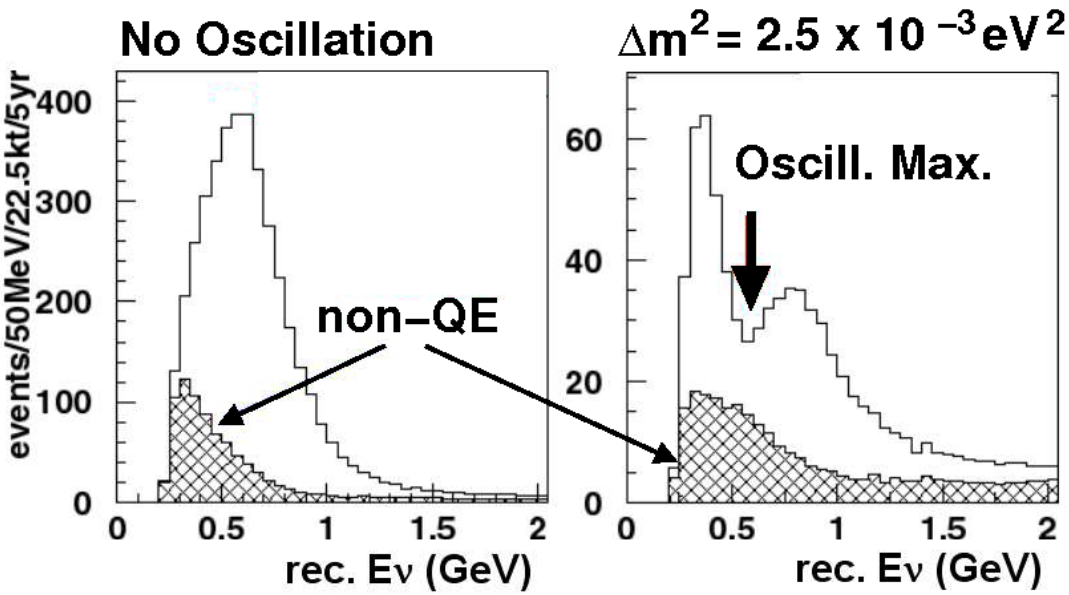




SHINE (NA49 upgraded to NA61)

- $\pi^\pm$, $K^\pm$ & $K^0$ prod.
- Protons on Carbon target: Matched to T2K
- Understand hadron production: Use for $R_{N/F}$

# $\nu_\mu$ disappearance: $\theta_{23}$ and $\Delta m^2_{23}$



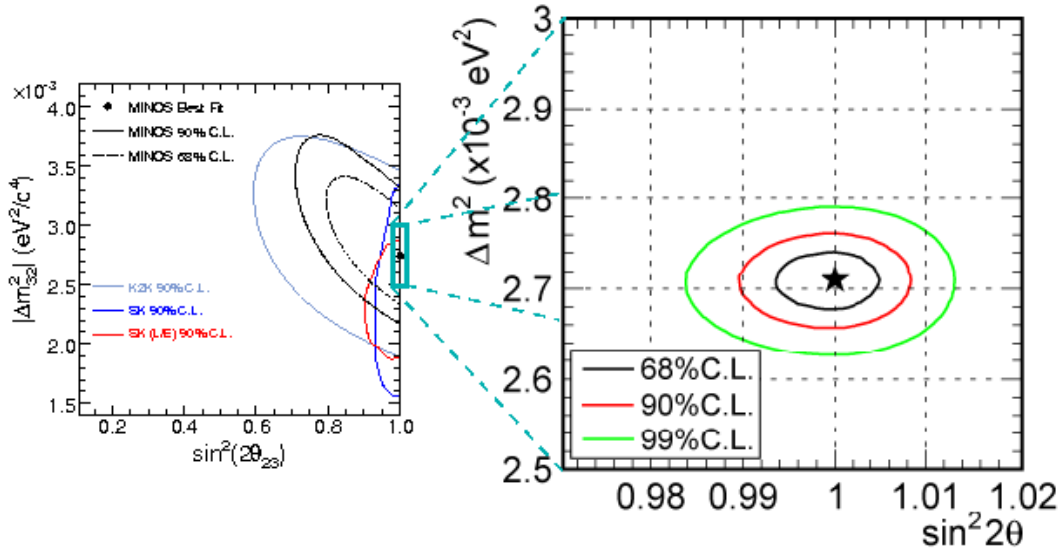

## Achieved sensitivity

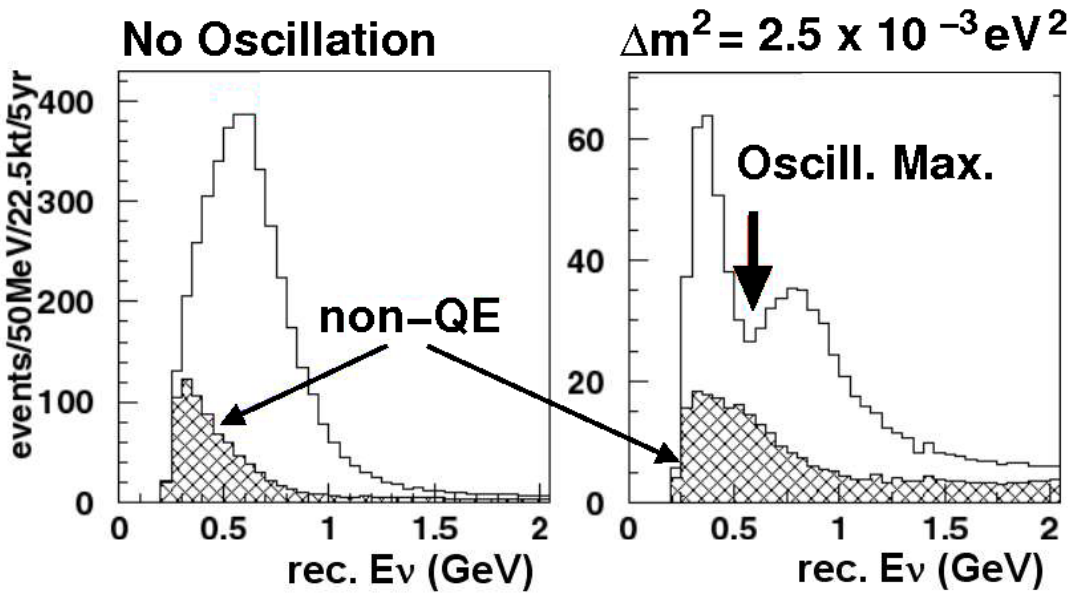
$\delta(\sin^2 2\theta_{23}) \simeq 0.01$

$\delta(\Delta m^2_{23}) < 10^{-4}$ eV$^2$

- 5 years $\times 0.75$ MW
- Systematics controlled to 25% level

# $\nu_\mu$ disappearance: $\theta_{23}$ and $\Delta m^2_{23}$

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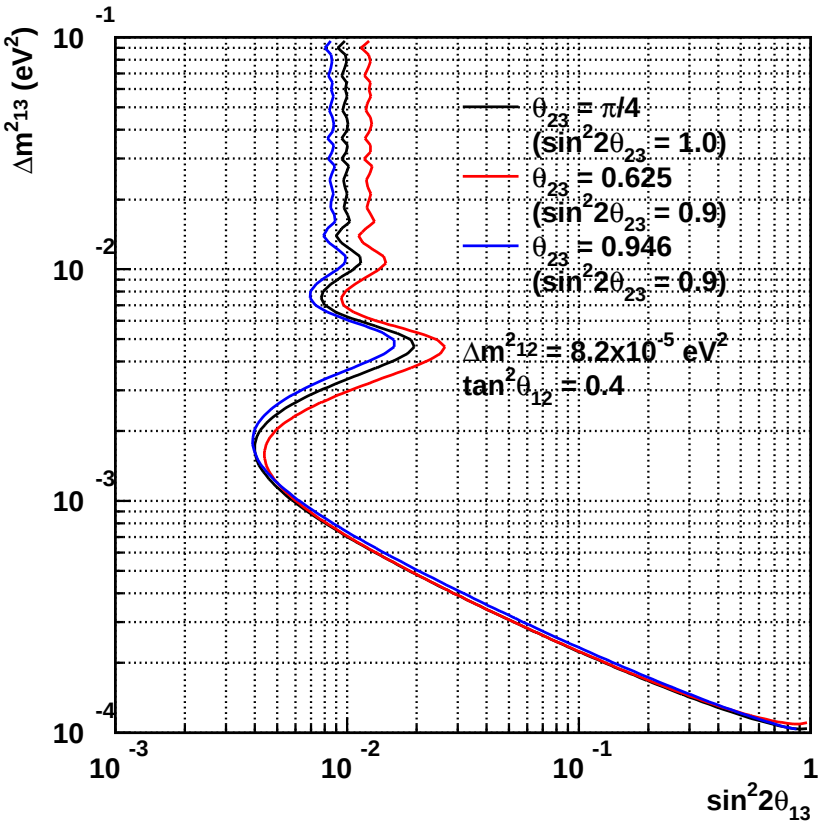
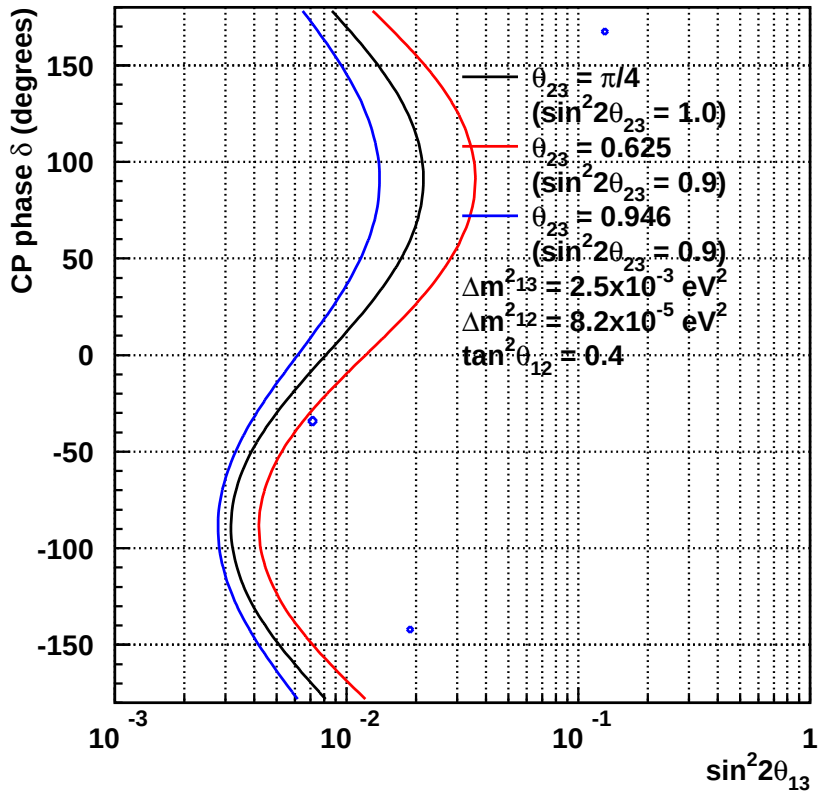
# $\nu_e$ appearance: $\theta_{13}$

- 5 years $\times$0.75 MW
- Error on background estimation at 10%




$\sin^2 2\theta_{13} < 0.008$ (90% C.L.)
for: $\delta = 0$, $\Delta m^2_{13} = 2.5 \times 10^{-3}$ eV$^2$, $\sin^2 2\theta_{23} = 1$

- Factor 10 improvement on CHOOZ limits (for any $\delta$)

# Possible Future Projects

See significant $\nu_\mu \rightarrow \nu_e$ with T2K:

Then:

- Refine $\nu_\mu \rightarrow \nu_e$ measurement ($\sin^2 2\theta_{13}$)
- Try CP violation physics!

Must:

- Improve $\nu$ beam intensity
  - Proton beam intensity
- Improve far detector
  - Volume
  - Technology
  - Baseline/angle

# Oscillation probability

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

Where:

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

$$T_2 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

$$T_3 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

$$T_2 - T_3 = \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

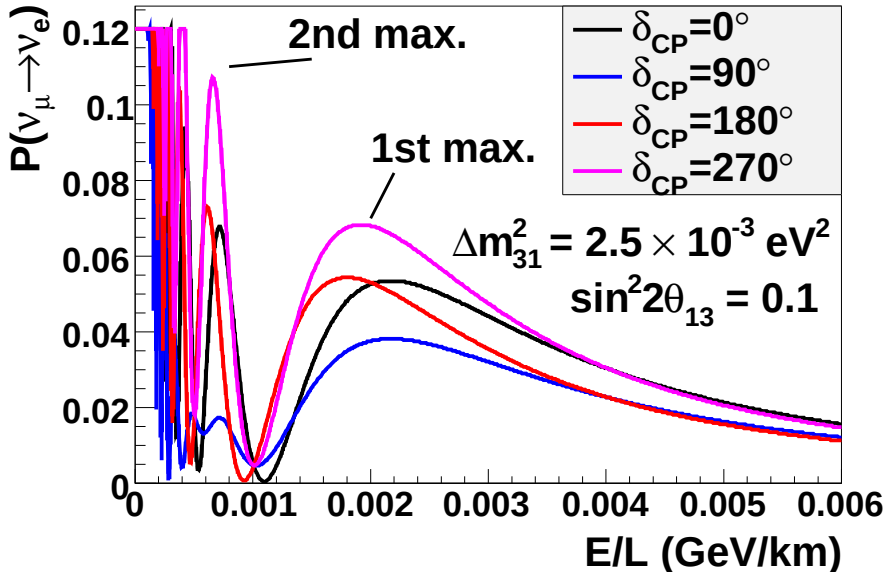
$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2} \quad \leftarrow \text{Solar}$$

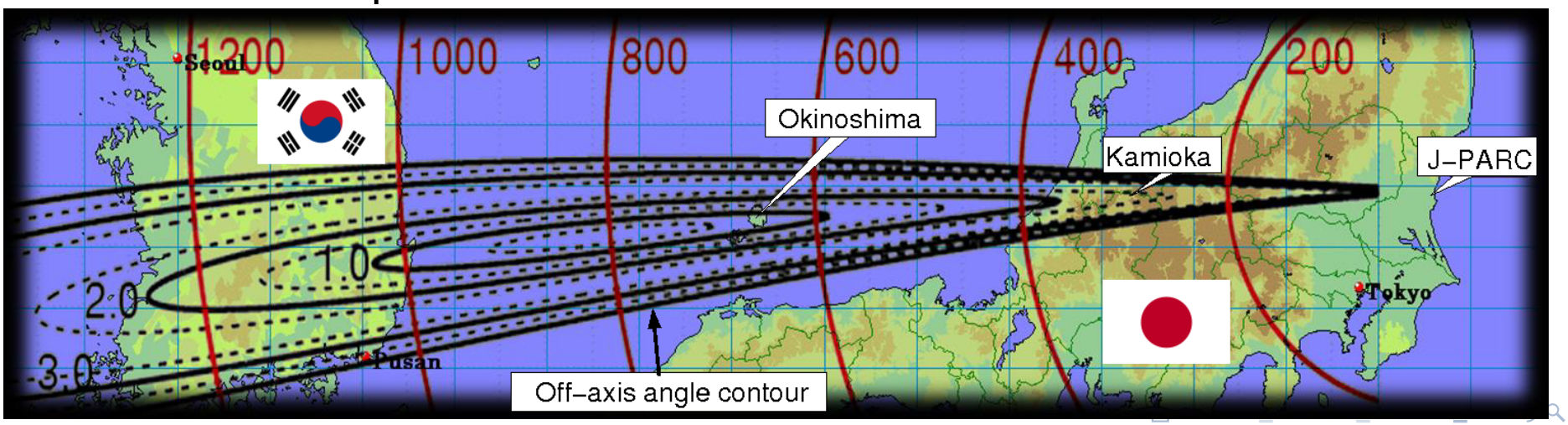
And:

$$A \equiv \frac{2EV}{\Delta m^2_{31}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

# Detector/Beamline Configuration

- $\sin^2 2\theta_{13} \Rightarrow$ Gross osc. amp.
- $\delta_{CP}$ affects osc. amplitude
- $\nu \rightarrow \bar{\nu}$:$\delta_{CP} \rightarrow -\delta_{CP}$
- To measure $\delta_{CP}$ need either
  - Both 1st & 2nd maximum
  - Both $\nu_\mu$ and $\bar{\nu}_\mu$ beams
- See both max's using diff. $E/L$
- Recall $E$ varies with Off-axis angle
- Panned beam power: 1.66 MW



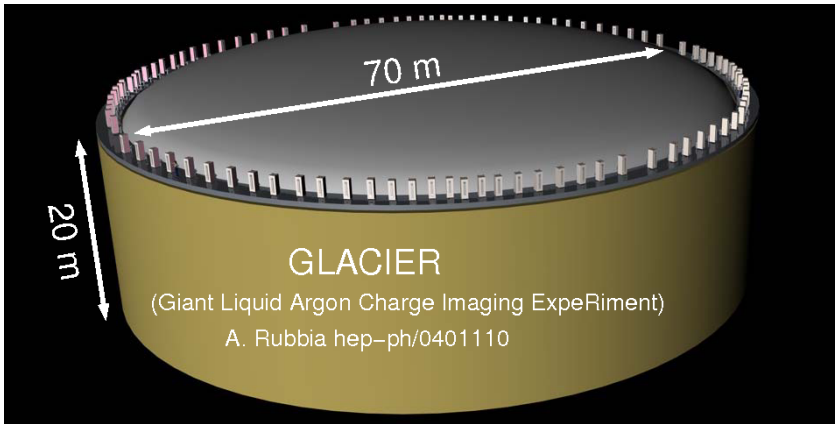



# Okinoshima (A. Bueno et al, NP08)

## Features

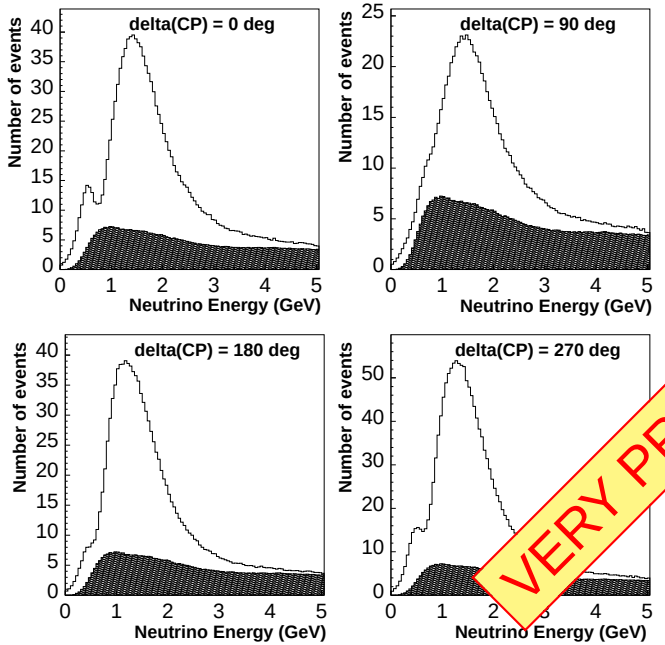
- Liquid Argon TPC at 600 km
- Small off-axis angle (0.76°)
  - ⇒ Some energy spread
  - ⇒ 1st & 2nd maximum
- Excellent spacial resolution
  - ⇒ Suppress $\pi^0$ background

## Detector Concept

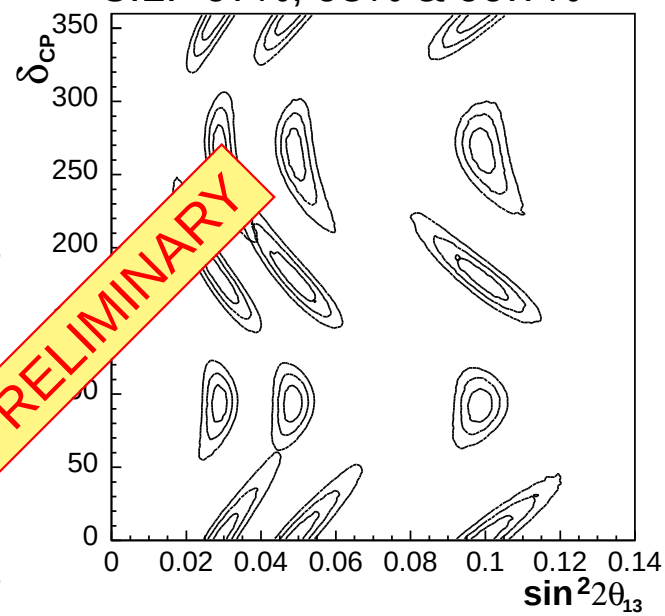



## Simulation

- $\sin^2 2\theta_{13} = 0.03$
- 5 years with $\nu_\mu$ beam
- 100 kt fiducial mass
- $\sigma(E_\nu) = 100$ MeV

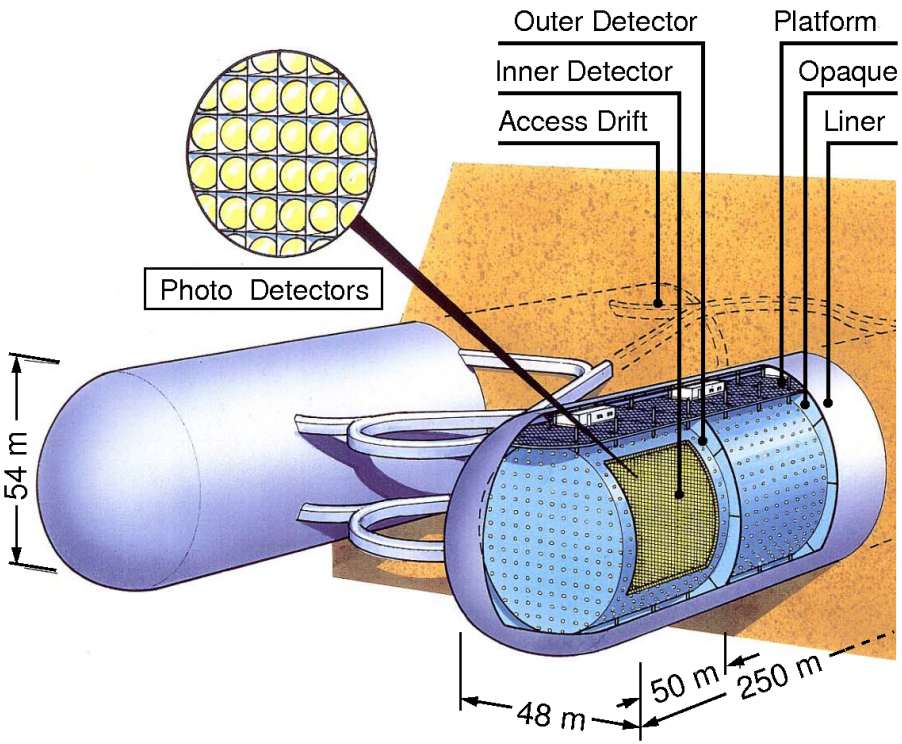



C.L.=67%, 95% & 99.7%

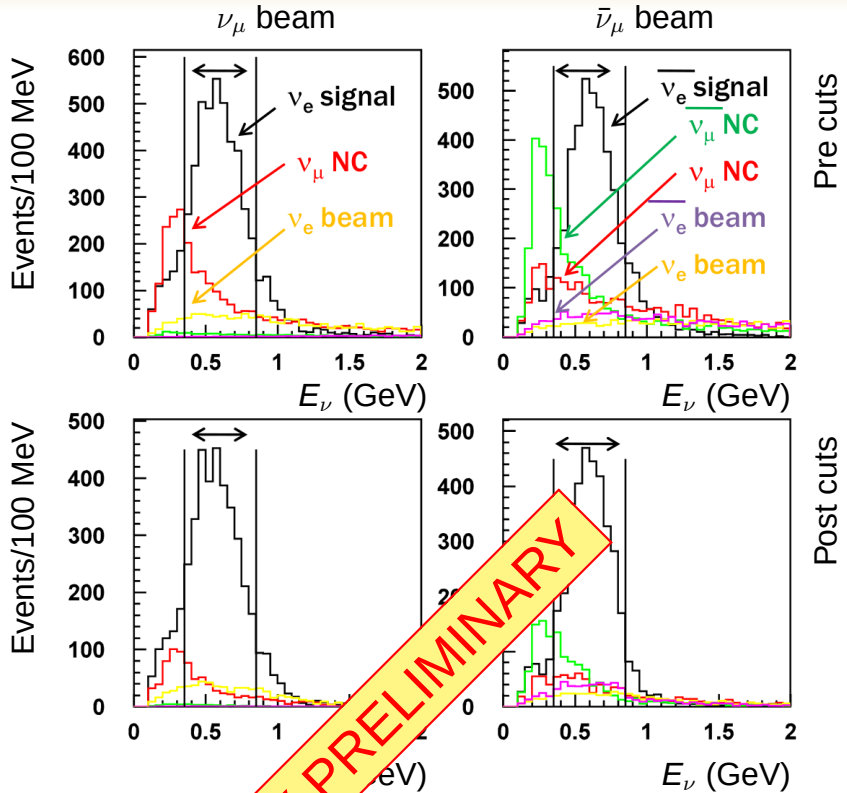


# Kamioka: "Hyper-K" (K. Kaneyuki, NP08)

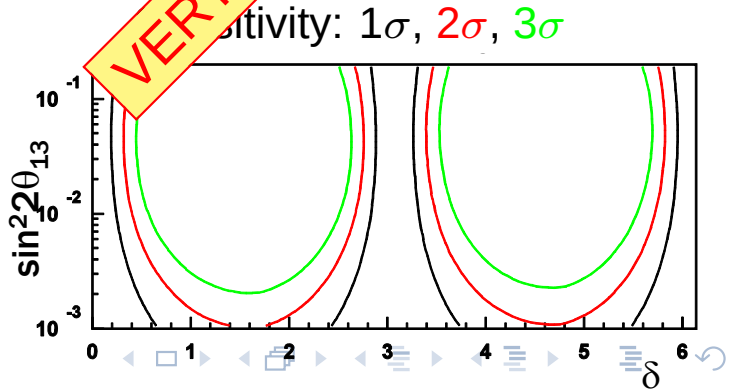
- Water Cerenkov
- 1000 kt: $2 \times 270$ kt fiducial ($\simeq 24\times$ Super-K)
- $0.2 \times 10^6$ PMTs
- 2.2 yr $\nu_\mu$, 7.8 yr $\bar{\nu}_\mu$




For $\sin^2 2\theta_{13} = 0.1$

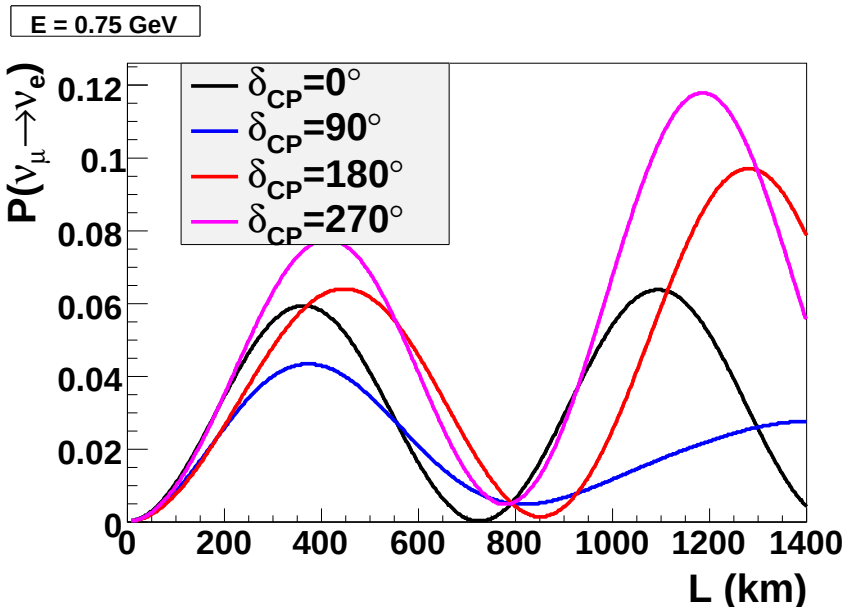


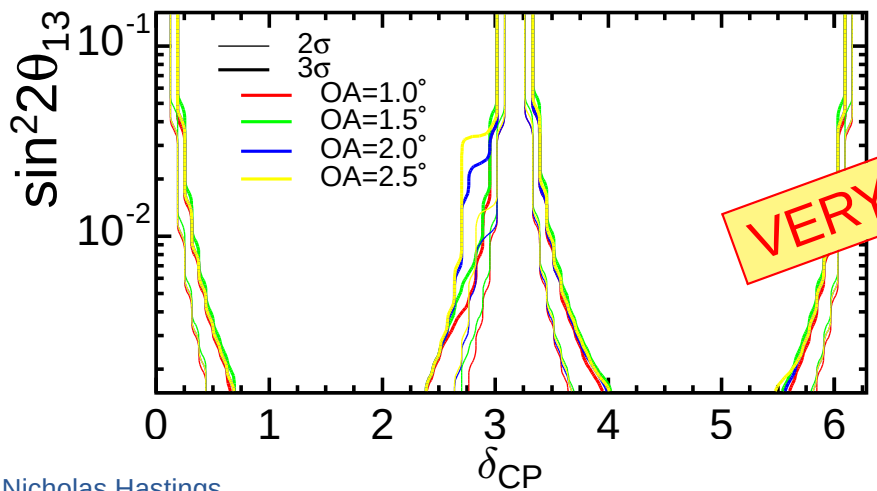

VERY PRELIMINARY



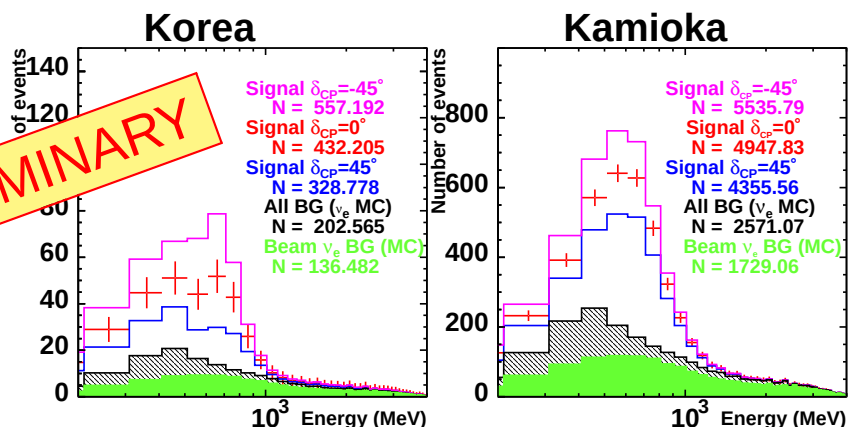
# Korea: "T2KK" (F. Dufour, NP08)

- $\theta_{\mathrm{OA}}^{\mathrm{Korea}} = \theta_{\mathrm{OA}}^{\mathrm{Kamioka}} = 2.5\,^{\circ}$
  - $\Rightarrow E \simeq 0.75\ \mathrm{GeV}$
- Two similar detectors
  - "Near Detector": Kamioka (295 km)
    $\Rightarrow$ Sees 1st osc. max
  - "Far Detector": Korea ($\sim$ 1000 km)
    $\Rightarrow$ Sees 2nd osc. max
- Ie. put one of the Hyper-K detectors in Korea
- 5 yr $\nu_\mu$, 5 yr $\bar{\nu}_\mu$




VERY PRELIMINARY




For $\sin^2 2\theta_{13} = 0.04$

# Summary

- New accelerator facility: Large number of protons on target
- Off-axis beam: Narrow $E_\nu$ distribution tuned to oscillation maximum
- Extensive suite of beam monitors/near detectors
- Well established far detector
- Physics Prospects
  - Search for $\nu_e$ appearance: order magnitude improvement on $\sin^2 2\theta_{13}$
  - Precision measurements: $\delta(\sin^2 2\theta_{23}) \simeq 0.01$, $\delta(\Delta m^2_{23}) < 10^{-4}\ eV^2$
- T2K facility at J-PARC well underway
- Start Neutrino beam commissioning April 2009
- Towards the future
  - If $\nu_\mu \rightarrow \nu_e$ is large: look for *CPV*
  - Must upgrade the beam power
  - Various promising detector/beamline options under study

# Contents

Introduction
- The Current Situation

T2K
- Neutrino Beam
- Tokai Site
- Analysis
- $\nu_\mu$ disappearance: $\theta_{23}$ and $\Delta m^2_{23}$
- $\nu_e$ appearance: $\theta_{13}$

Possible Future Projects
- Detector/Beamline Configuration
- Detector Options

Summary

# Supplementary Material

T2K Physics Goals
Backgrounds
$\nu_\mu$ systematic error requirements
$\nu_e$ appearance
ND280
2 km Proposal
Future Detector Scenarios
Beam Upgrade
Approved Integrated Beam
Target
Mass Hierarchy
$P(\nu_\mu \rightarrow \nu_e)$ Terms (Matter effect off)
$P(\nu_\mu \rightarrow \nu_e)$ Terms (Matter effect on)
$P(\nu_\mu \rightarrow \nu_e)$ Terms (Matter effect on, $\Delta m^2_{13} < 0$)
Comparison of $\theta_{13}$ sensitivities

# Goals

## T2K Goals

- Refine $\nu_\mu$ disappearance:

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\Phi_{23}$$
$$\equiv 1 - \sin^2 2\theta_{\mu\tau}\sin^2\Phi_{23}$$

- Measure $\nu_e$ appearance:

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Phi_{23}$$
$$\equiv \sin^2 2\theta_{\mu e}\sin^2\Phi_{23}$$

Where:

$$\Phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$
$$= \frac{1.27(\Delta m^2_{ij}/\mathrm{eV}^2)(L/\mathrm{km})}{E/\mathrm{GeV}}$$

## Future Goals

- Refine $\nu_e$ appearance
- IF $\nu_\mu \to \nu_e$ is sufficiently large:
  - look for *CPV*

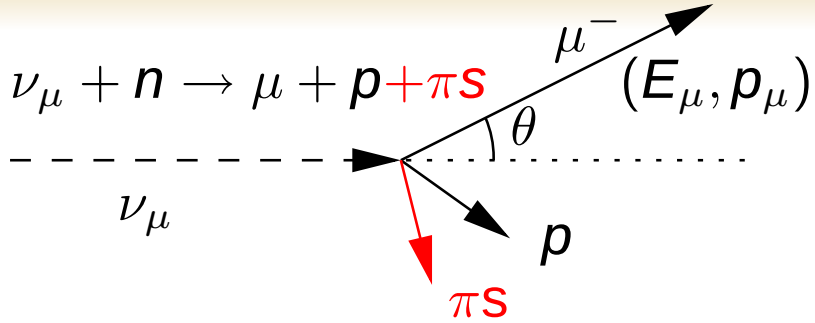
Eg.

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$
$$= \frac{\Delta m^2_{12}}{4E}\frac{\sin 2\theta_{12}}{\sin\theta_{13}}\sin\delta$$

# Backgrounds

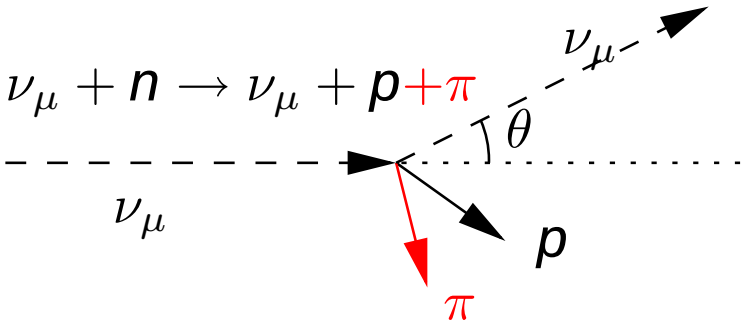
## CC-nQE

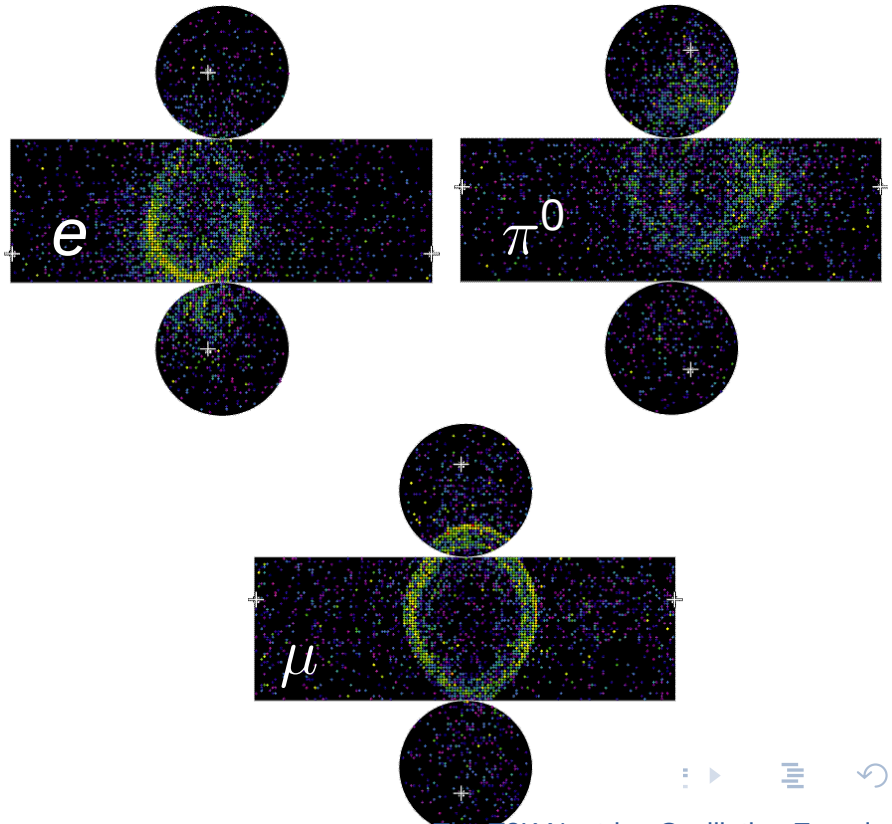
- Incorrect $E_\nu^{\text{rec}}$ determination




## Neutral Current (NC)

- $\pi^0$ can look like electron
- Hampers $\nu_\mu \rightarrow \nu_e$ search



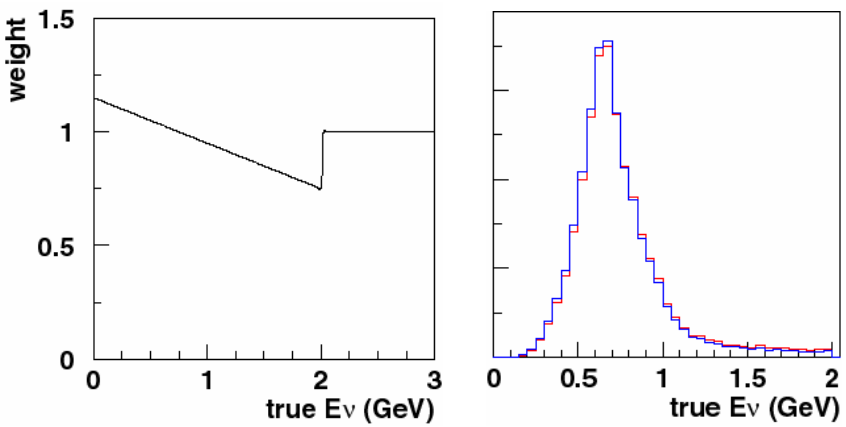

## Other

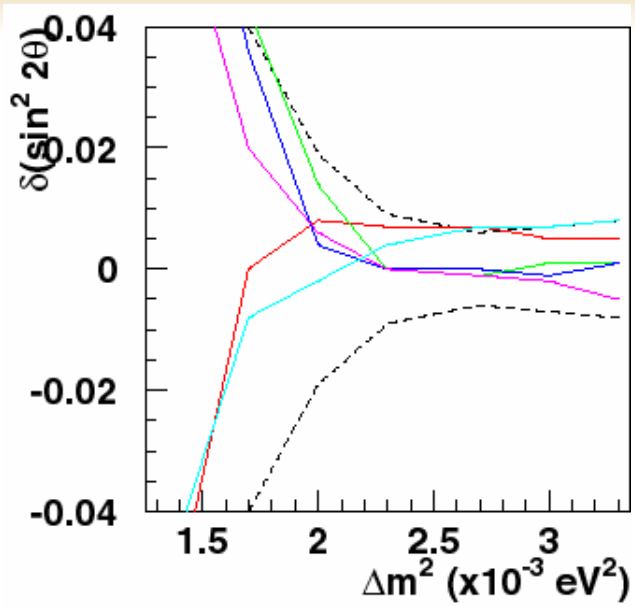
- Intrinsic $\nu_e$ content in beam
- Muon/Electron separation

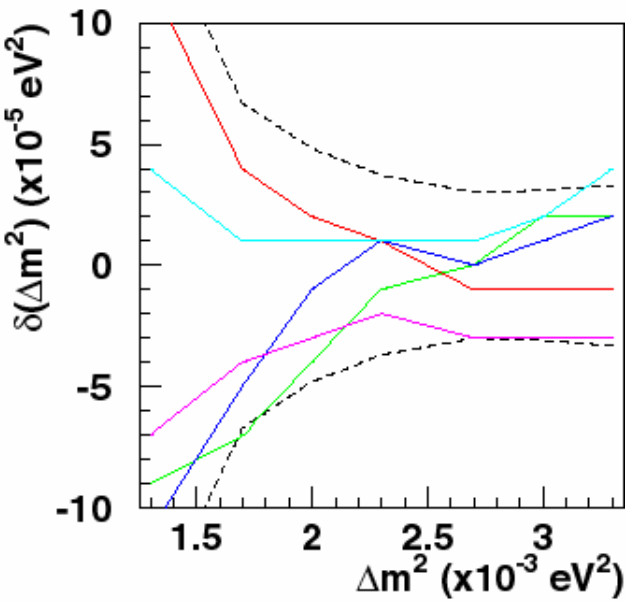
# $\nu_\mu$ systematic error requirements

Measurement error remains statisics limited

| Source | Size |
|---|---|
| Non-QE/QE Ratio | $< 5\%$ |
| Energy Scale | $< 2\%$ |
| Flux Normalisation | $< 10\%$ |
| Flux Width | $< 10\%$ |
| Flux Shape | $< 20\%$ |



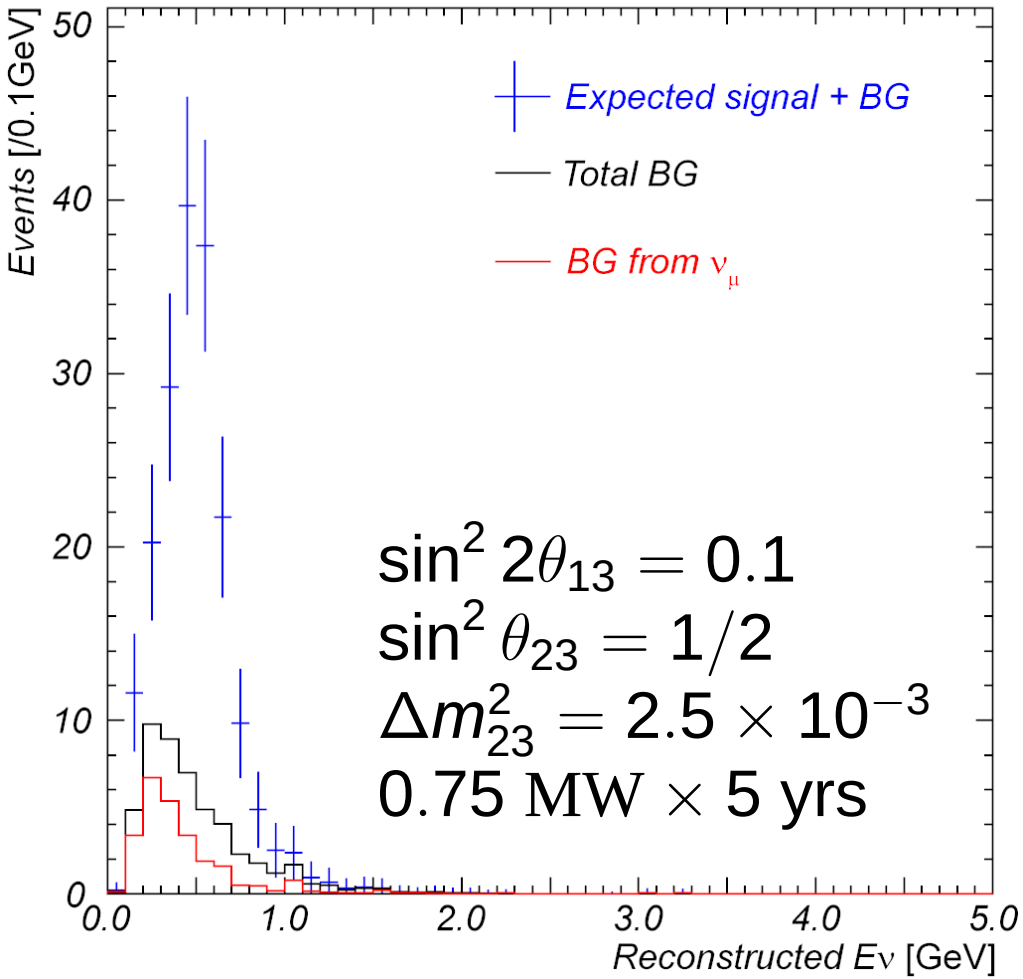
# $\nu_e$ appearance

- Look for excess of 1 ring *e* events
- Expected numbers at SK with T2K (0.75 $\mathrm{kW} \times$ 5 years)

| $\sin^2 2\theta_{13}$ | Backgrounds | | | Signal |
|---|---|---|---|---|
| | $\nu_\mu$ | Beam $\nu_e$ | total | |
| 0.1 | 10 | 13 | 23 | 103 |
| 0.01 | | | | 10 |

- Dominant backgrounds
  - Intrinsic $\nu_e$ in beam: irreducible
  - $\nu_\mu$ induced NC-$\pi^0$: study with near detector

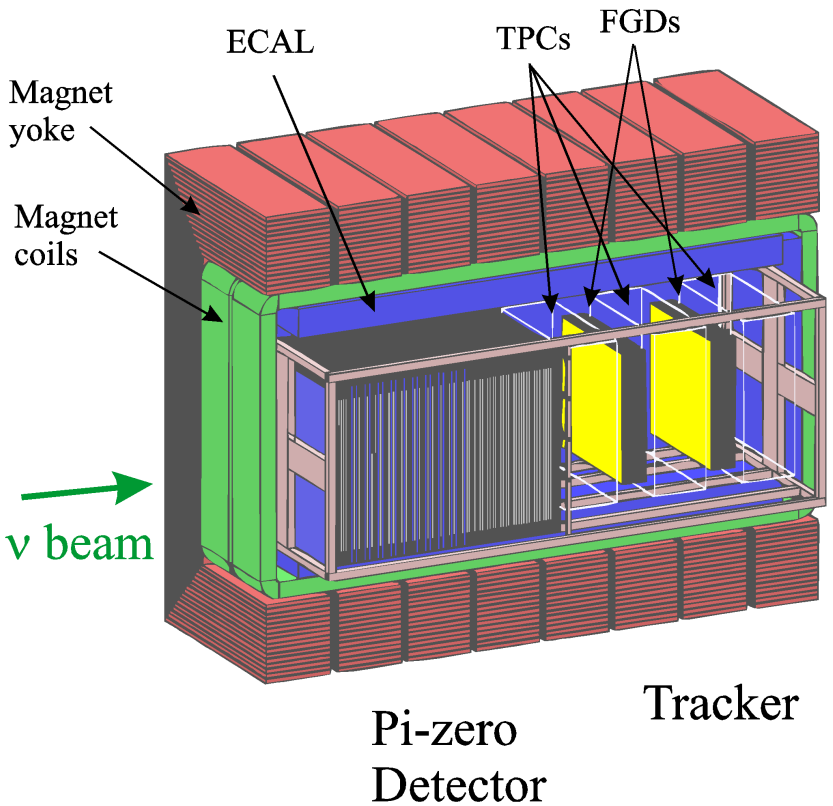
# $\nu_e$ appearance



# ND280 Pit

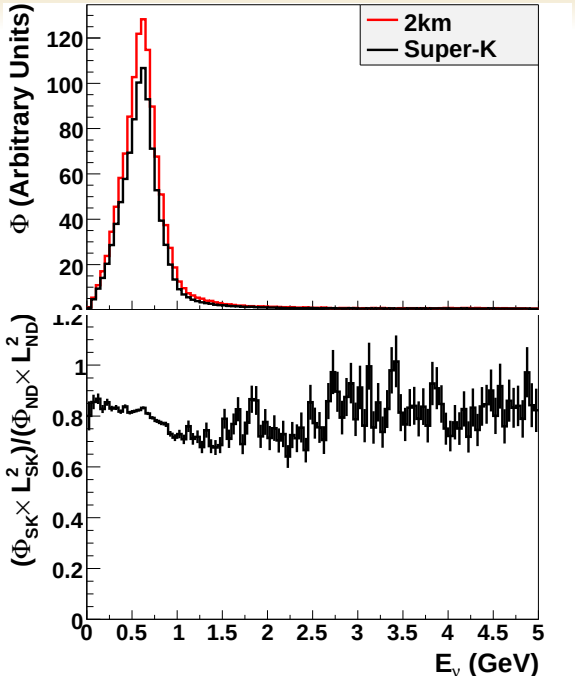
# ND280 Detectors

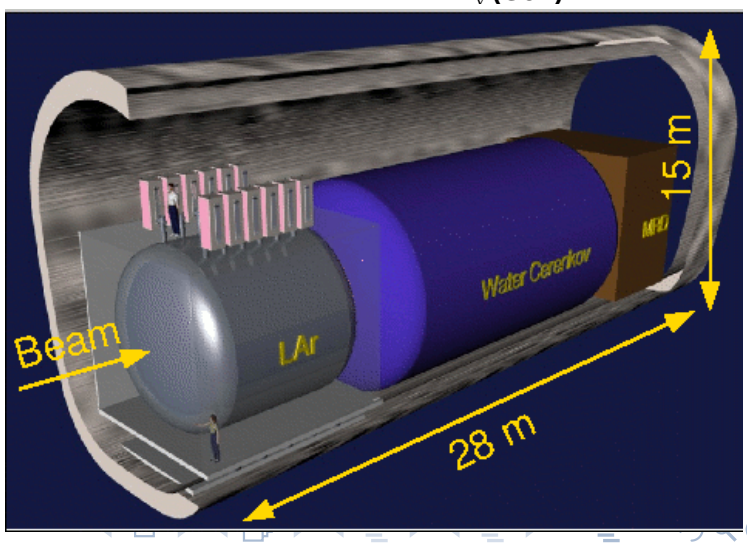
- Pi-zero detector (P0D)
  - measures NC-$\pi^0$ interactions
- Tracker: fine-grained detector (FGD) and time projection chambers (TPC)
  - measures CC interactions
- Electromagnetic calorimeter (ECAL)
  - detects EM activities coming from P0D/Tracker
- Side muon range detector (SMRD)
  - measures side-going muon energy
- All housed in UA1 magnet
  - $B = 0.2$ T



# 2 km Proposal

- Additional near detector under consideration
- Strengthen Super-K flux prediction
  - Measure flux at 2 km
  - Almost same flux as at 295 km
  - Same target material & detector/analysis tech.
- Check ND280/NA61 prediction
- Combine with ND280/NA61 measurements
  - Further reduce systematic errors
  - Better understand $\nu_e$ backgrounds



# Future Detector Scenarios

| Scenario | I: Okinoshima | II: Kamioka | III: Korea |
|---|---|---|---|
| Baseline (km) | 660 | 295 | 295 & 1000 |
| Off-Axis angle | 0.8° | 2.5° | 2.5° & 2.5°(or 1°) |
| Method | $E_{\nu_e}$ shape | $N_{\nu_e}/N_{\bar{\nu}_e}$ | $E_{\nu_e}$ shape |
| Beam | 5 years $\nu_\mu$, results dep't | 2.2 years $\nu_\mu$, 7.8 years $\bar{\nu}_\mu$ | 5 years $\nu_\mu$, 5 years $\bar{\nu}_\mu$ |
| Detector Type | Liq. Ar TPC | Water Cherenkov | Water Cherenkov |
| Detector Mass | 100 kt | $2 \times 270$ kt | 270 kt & 270 kt |

# Beam Parameters

| | Day 1 (till July 2010) | Next Step | KEK Roadmap | Ultimate |
|---|---|---|---|---|
| Power(MW) | 0.1 | 0.45 | 1.66 | ? |
| $E$(GeV) | 30 | 30 | 30 | |
| Rep. Cycle(s) | 3 | 2–3 | 1.92 | |
| No. Bunch | 6 | 8 | 8 | |
| Particle/Bunch | $1.2 \times 10^{13}$ | $< 4.1 \times 10^{13}$ | $8.3 \times 10^{13}$ | |
| Particle/Ring | $7.2 \times 10^{13}$ | $< 3.3 \times 10^{14}$ | $6.7 \times 10^{14}$ | |
| $E_{\text{Linac}}$(MeV) | 181 | 181 | 400 | |

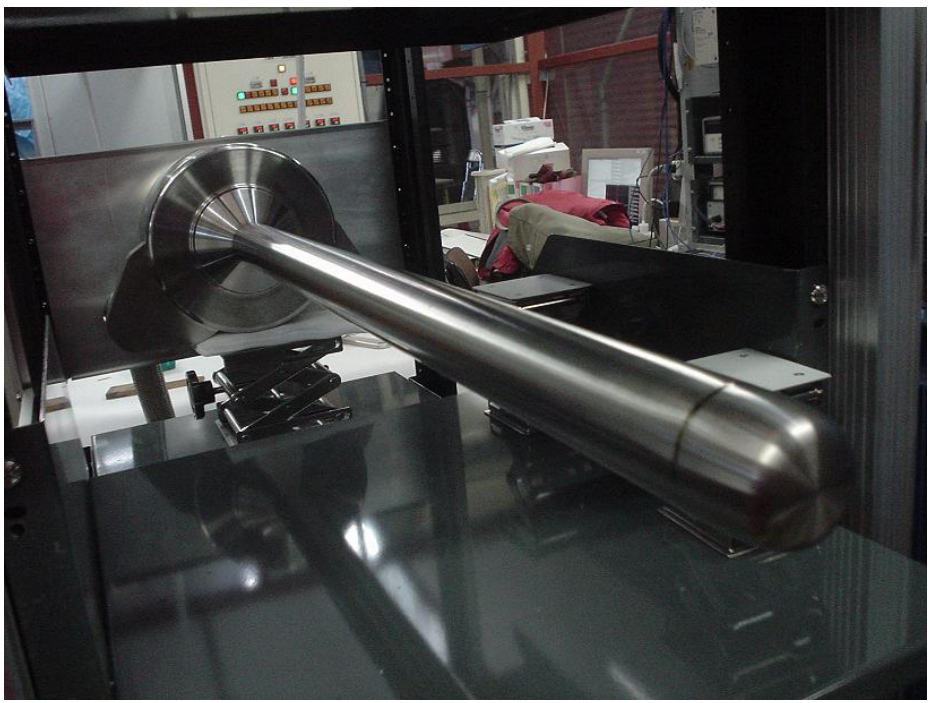
# Approved Integrated Beam

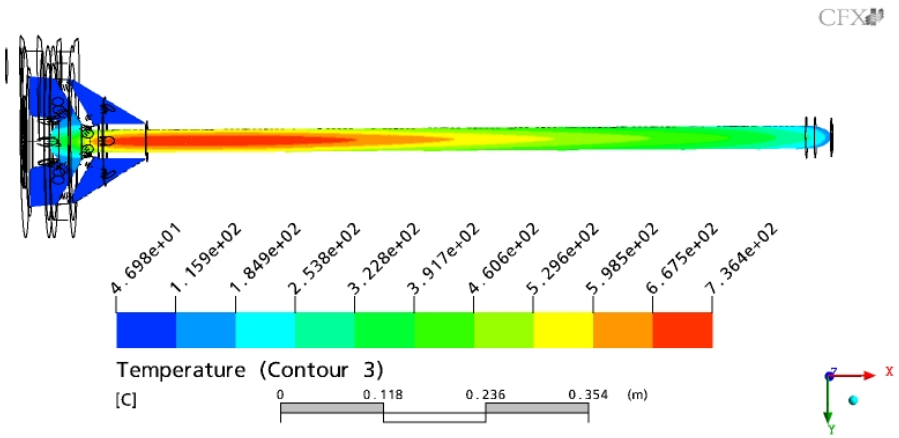
## T2K Proposal accepted by J-PARC PAC:

*We request total integrated beam power larger than 0.75* $\mathrm{MW} \times$ *15000* $\mathrm{h}$ *at any proton energies between 30* $\mathrm{GeV}$ *and 50* $\mathrm{GeV}$

- $15000\ \mathrm{h} = 5 \times 3000\ \mathrm{h} \simeq 5 \times 10^7\ \mathrm{s}$
- $\simeq 10^7\ \mathrm{s/year}$ run time ($\simeq \pi \times 10^7\ \mathrm{s/year}$ clock time)
- $\Rightarrow 0.75\ \mathrm{MW} \times 5\ \mathrm{year}$

# Target






- Isotropic Graphite (IG-430)
- Encapsulated in Ti alloy tube
- Prototype delivered Dec. 2007
- L = 90 cm, $\phi$=26 mm
- Forced flow helium gas cooling
- Full spec He gas flow achieved
- $\Delta T_{pulse} = 200\ ^{\circ}\mathrm{C}$

# Oscillation probability

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

Where:

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

$$T_2 - T_3 = \sin 2\theta_{12} \sin 2\theta_{23} (\cos \delta_{CP} \cos \Delta - \sin \delta_{CP} \sin \Delta) \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

$$= \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2} \quad \leftarrow \text{Solar}$$

And:

$$A \equiv \frac{2EV}{\Delta m^2_{31}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

# Oscillation probability

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

Where:

$$T_1 = \sin^2 \theta_{23} \sin^2 \Delta \quad \leftarrow \text{Atmospheric}$$

$$\begin{aligned} T_2 - T_3 &= \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \Delta \sin \Delta \\ &= -\sin 2\theta_{12} \sin 2\theta_{23} \Delta \sin[\Delta + (\delta_{CP} - \pi/2)] \sin \Delta \end{aligned}$$

$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2} \quad \leftarrow \text{Solar}$$

And:

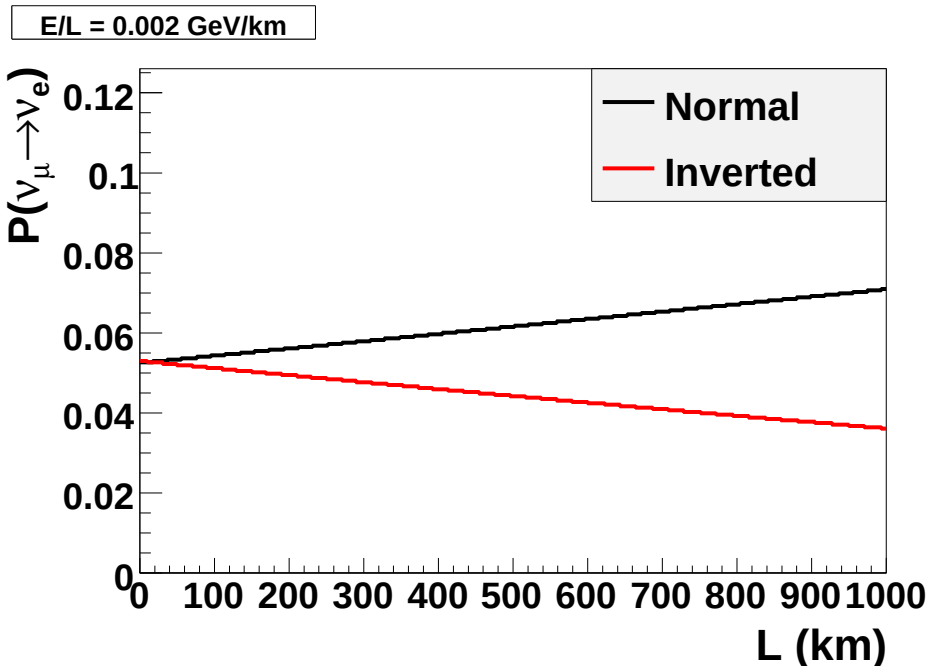
$$\lim : A \to 0, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

# Mass Hierarchy

- Matter effect enhances/decrease osc. amplitude for normal/inverted Hierarchy.
- Can employ different *L*'s to alter size of matter effect

## Example:

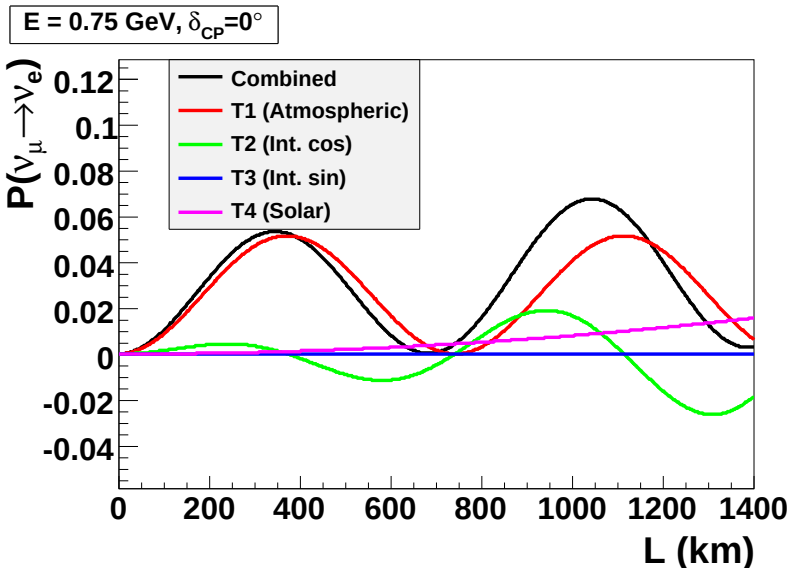
- Consider first oscillation max for: $\nu_\mu \rightarrow \nu_e$: $E/L = 0.002\ \mathrm{GeV/km}$
- Amplitude of first max changes with, L, and sign of $\Delta m^2_{13}$

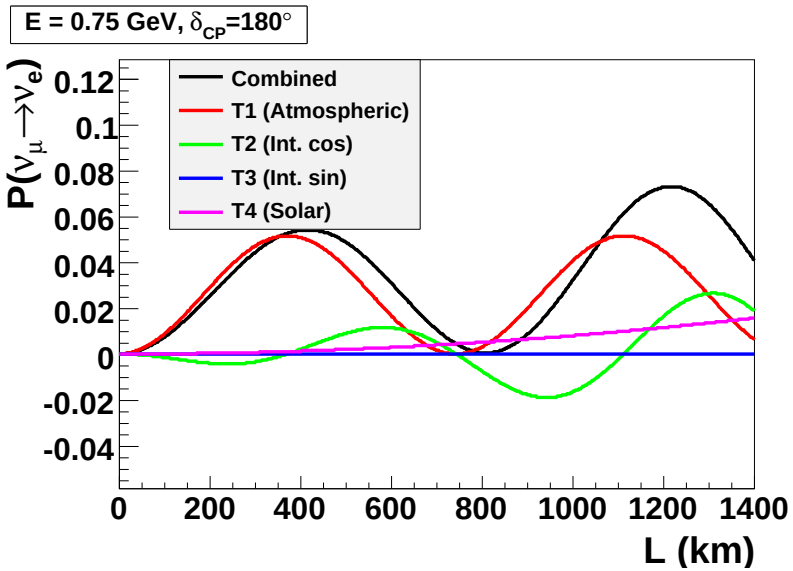


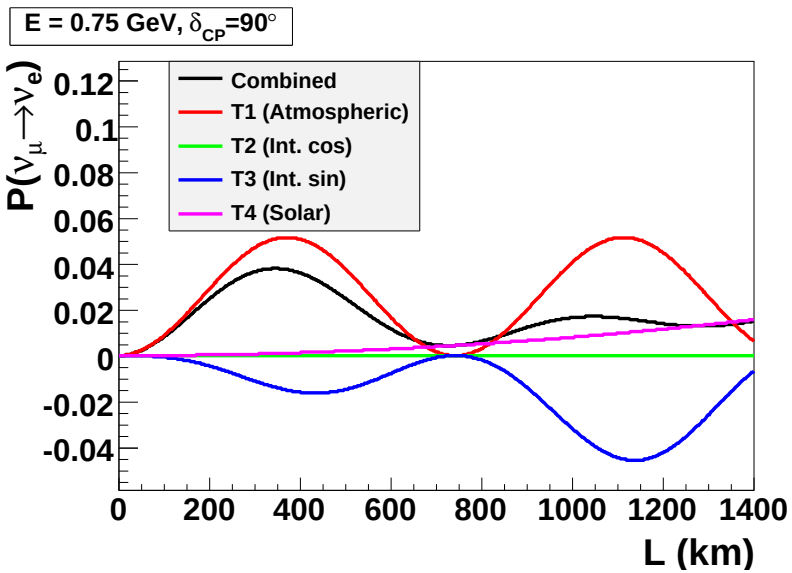

For details see:

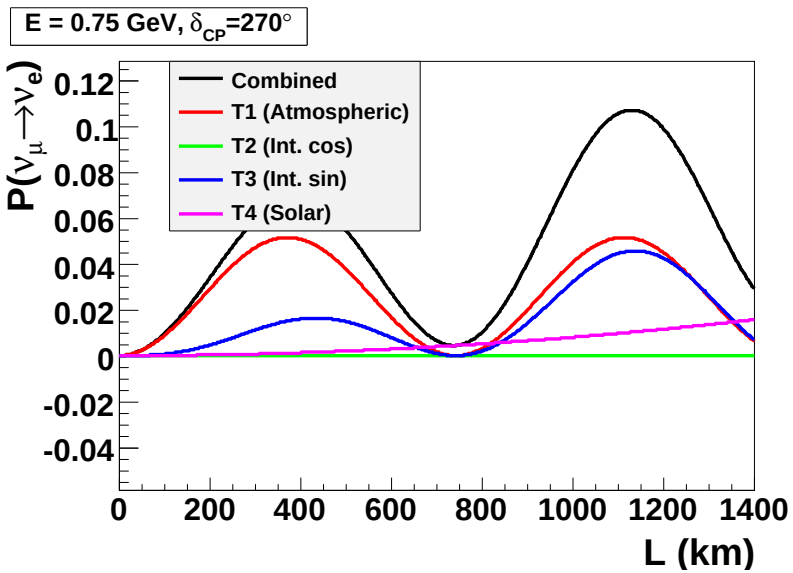
- Korea small off-axis angle option: reject wrong hierarchy at $4.7\sigma$ (hep-ph/0607255v3 section 5)
- Combining results from NO$\nu$A (L=810 km) and T2K(L=295 km) (hep-ph/0310023v1, hep-ph/0609031v1 )

# $P(\nu_\mu \rightarrow \nu_e)$ Terms (Matter effect off)

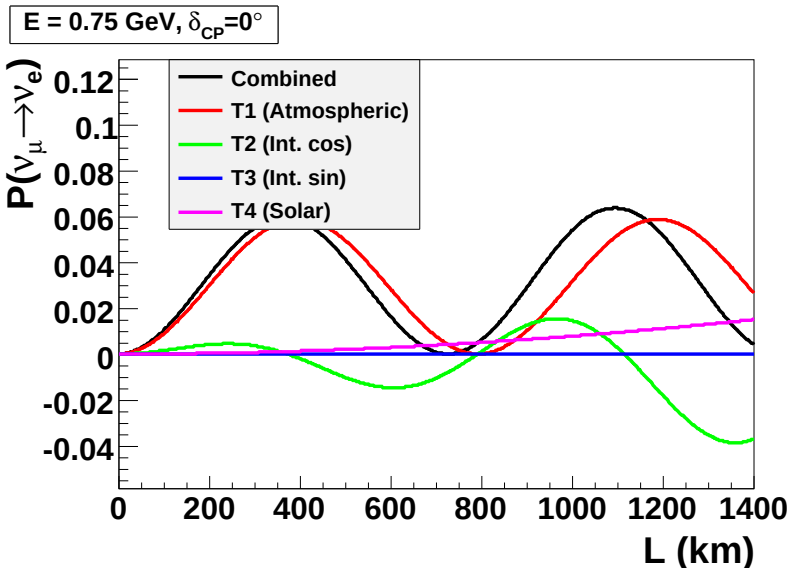


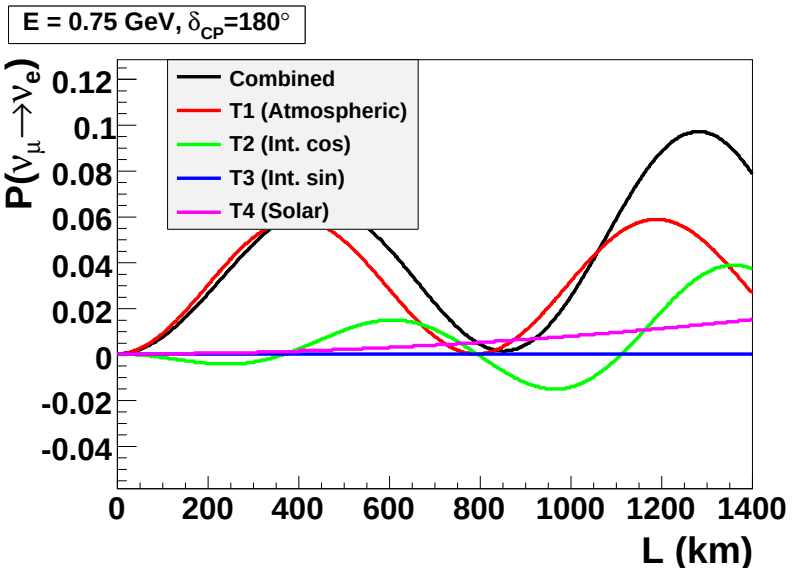



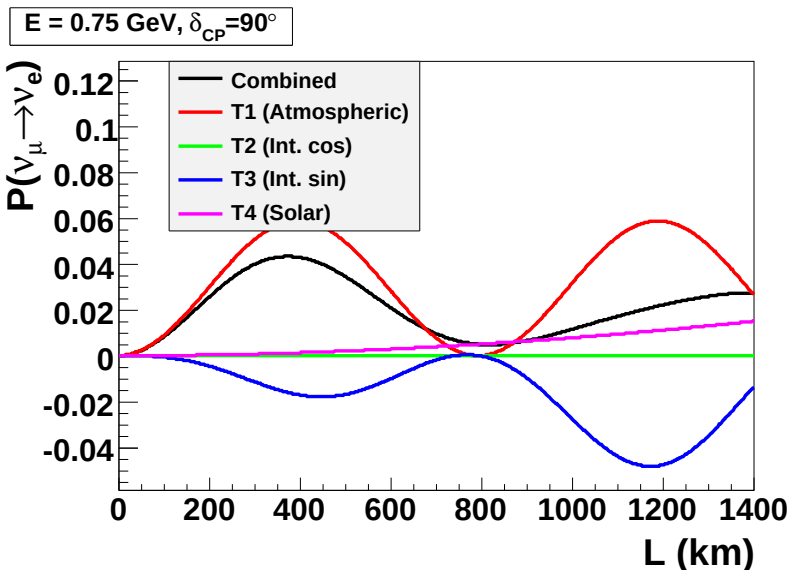



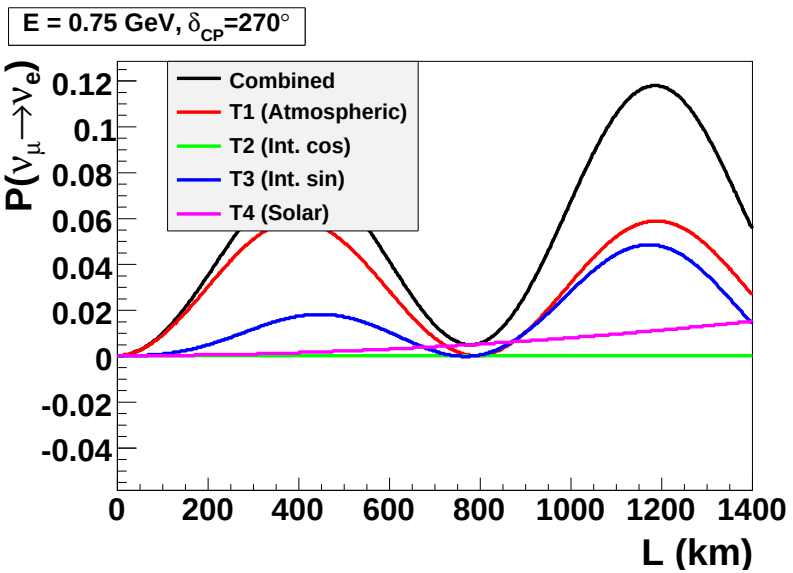



# $P(\nu_\mu \rightarrow \nu_e)$ Terms (Matter effect on)

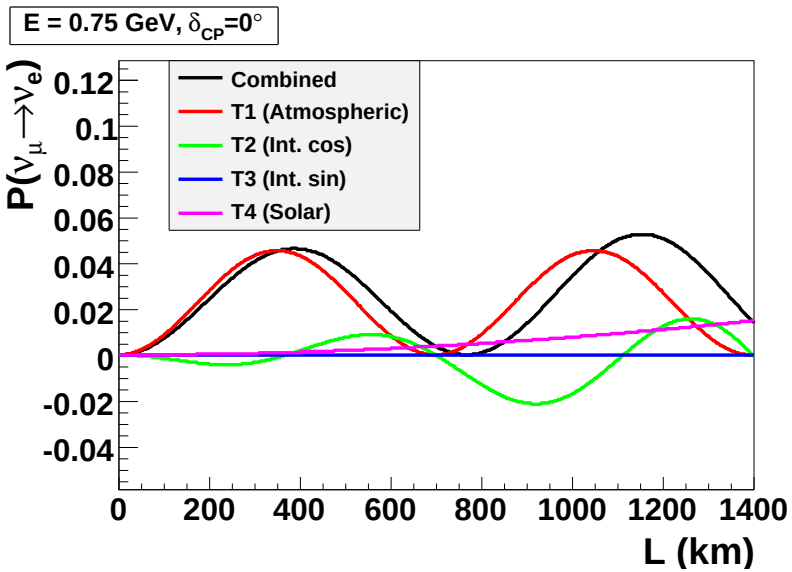


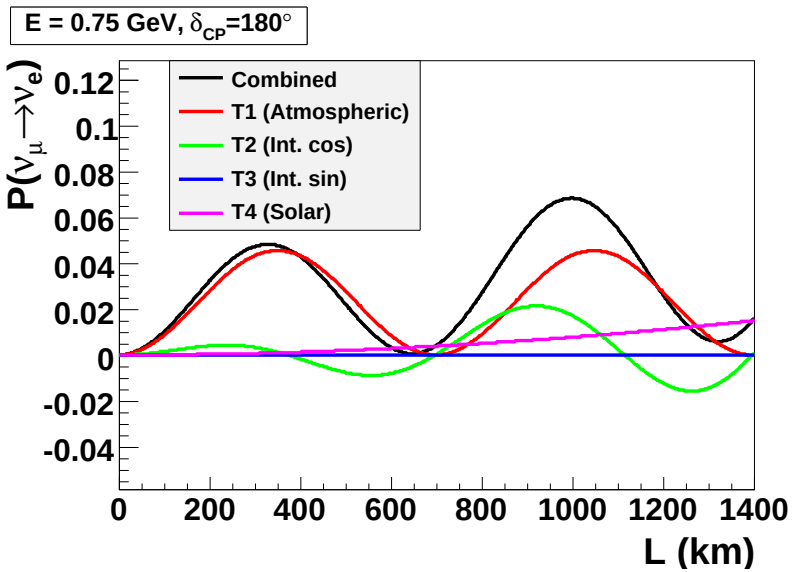



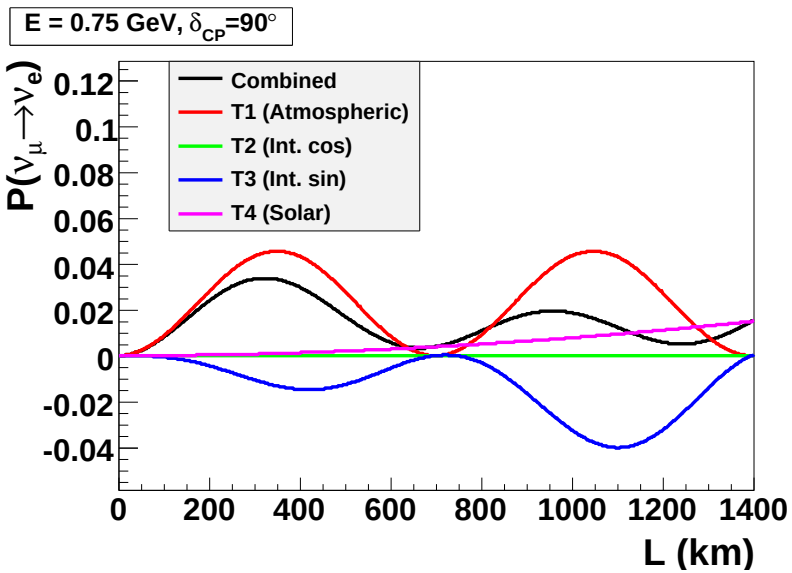



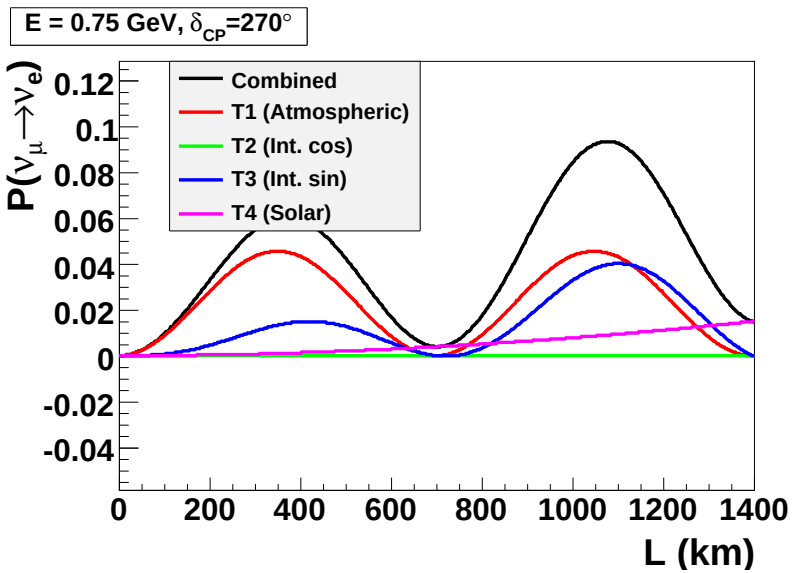



# $P(\nu_\mu \rightarrow \nu_e)$ Terms (Matter effect on, $\Delta m^2_{13} < 0$)



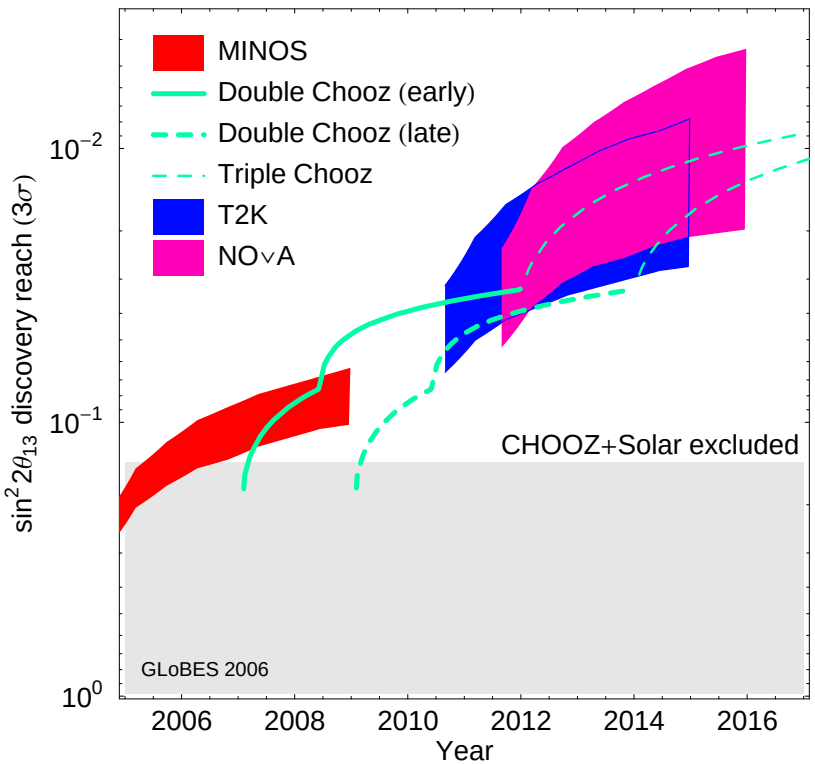



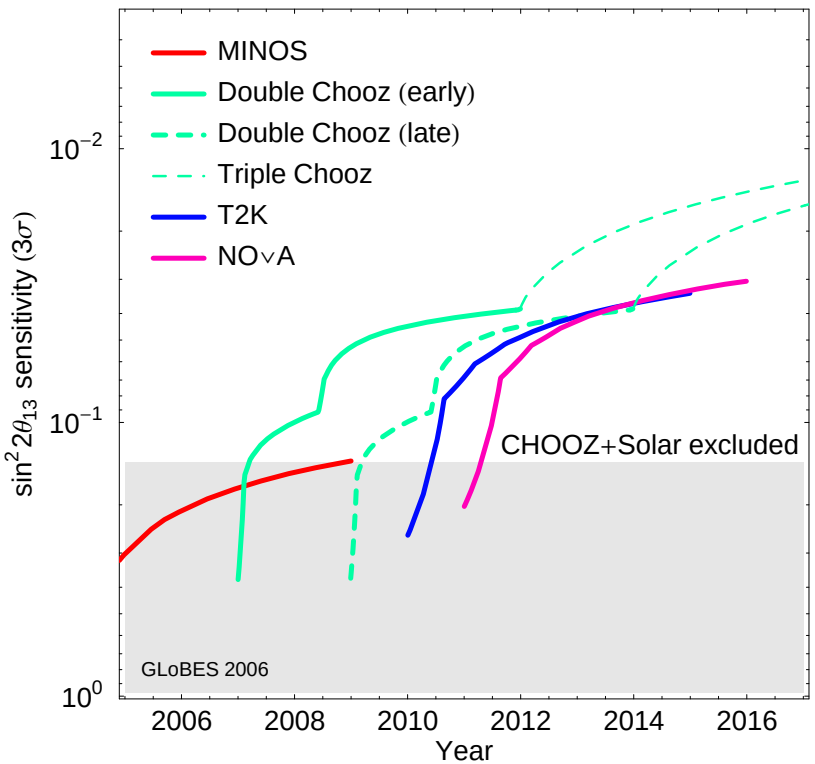



# Comparison of $\theta_{13}$ sensitivities

## $3\sigma$ discovery potential




## $3\sigma$ sensitivity




(from hep-ph/0601266)