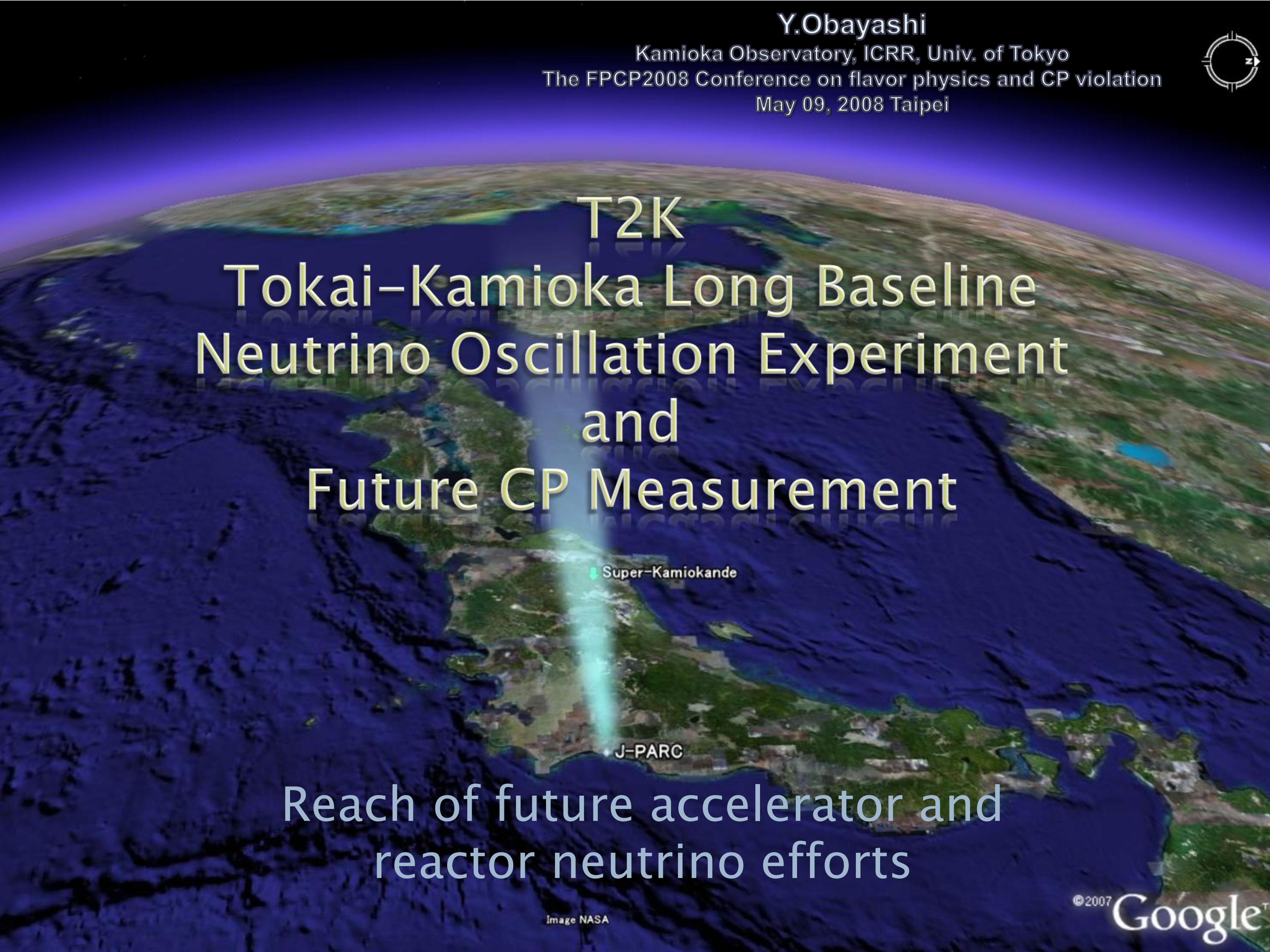
Y.Obayashi
Kamioka Observatory, ICRR, Univ. of Tokyo
The FPCP2008 Conference on flavor physics and CP violation
May 09, 2008 Taipei

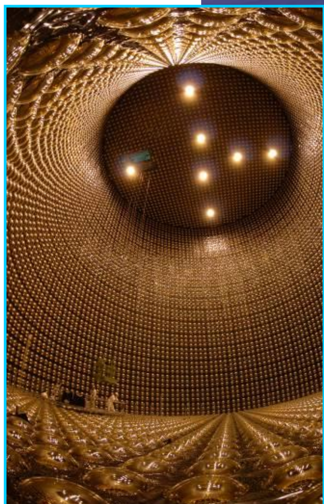
T2K
Tokai-Kamioka Long Baseline Neutrino Oscillation Experiment and Future CP Measurement

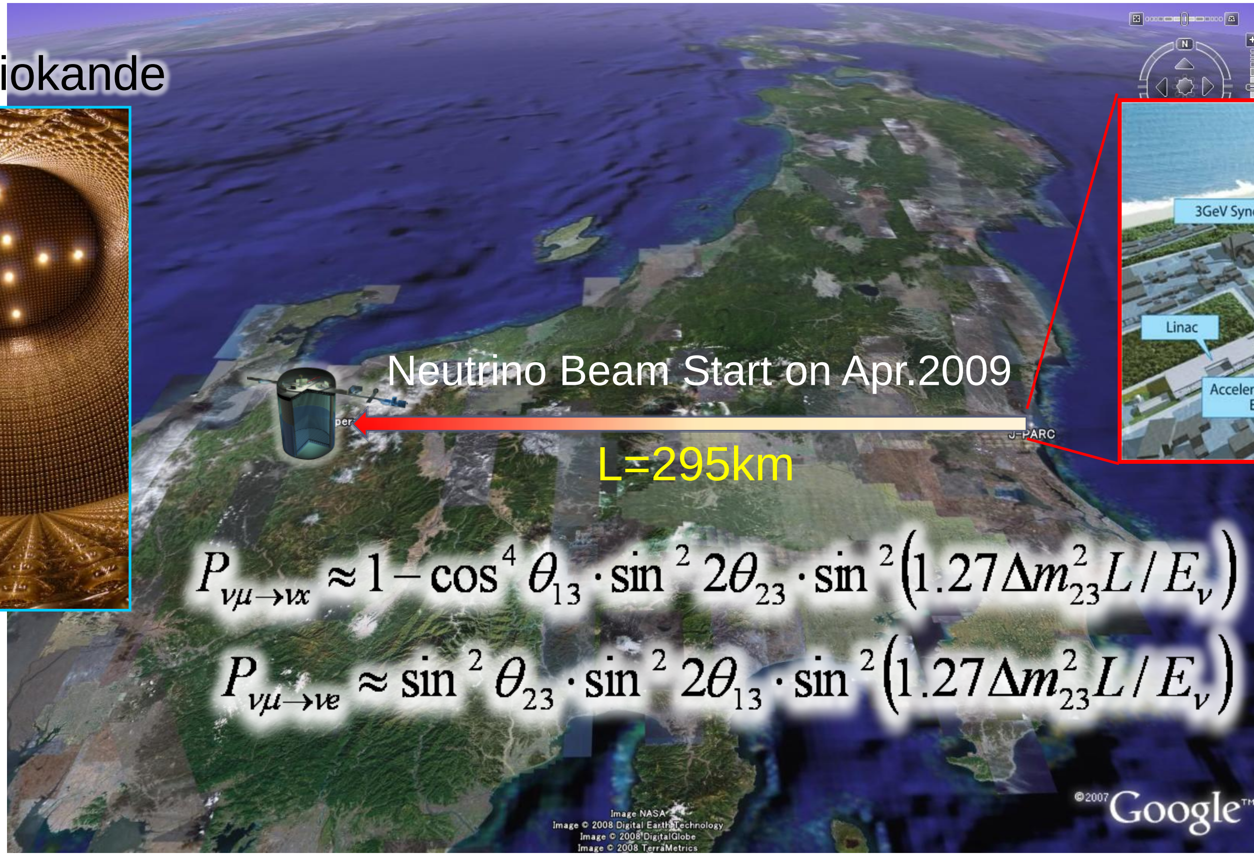


Reach of future accelerator and reactor neutrino efforts

T2K (Tokai to Kamioka) experiment

Super-Kamiokande





$$P_{\nu\mu\to\nu x} \approx 1 - \cos^4\theta_{13}\cdot\sin^2 2\theta_{23}\cdot\sin^2\left(1.27\Delta m_{23}^2 L/E_\nu\right)$$

$$P_{\nu\mu\to\nu e} \approx \sin^2\theta_{23}\cdot\sin^2 2\theta_{13}\cdot\sin^2\left(1.27\Delta m_{23}^2 L/E_\nu\right)$$

J-PARC @ Tokai

- High intensity ν_μ beam (~10^2xK2K) from J-PARC
- **Precise meas. of ν_μ disapp. → θ_{23}, Δm_{23}^2**
- **Discovery of ν_e app. → Determine θ_{13}**

current knowledge

$\sin^2 2\theta_{23} > 0.92$, $\Delta m_{23}^2 = (2\sim3)\times10^{-3}\,eV^2$

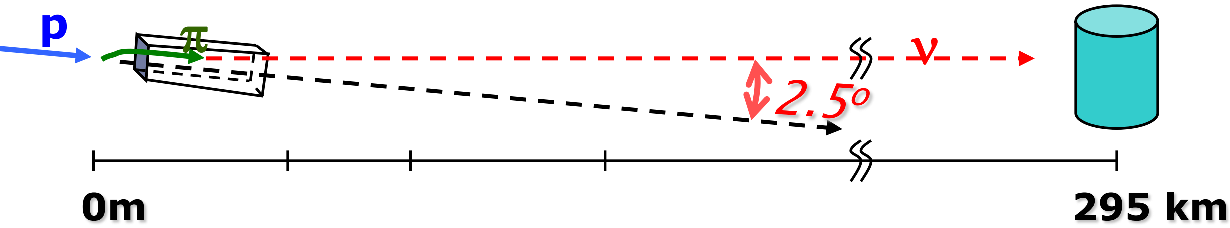
$\sin^2 2\theta_{13} < 0.15 @ \Delta m_{23}^2 = 2.5\times10^{-3}\,eV^2$

T2K Collaboration

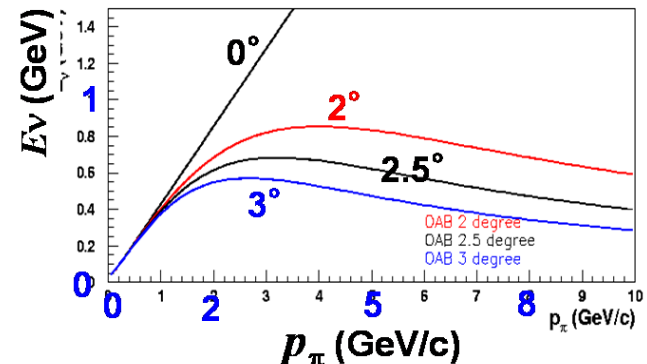
~400 members from 12 Countries

Japan, US, Canada, France, UK, Switzerland, Poland, Korea, Russia, Spain, Italy, Germany

Neutrino Beam

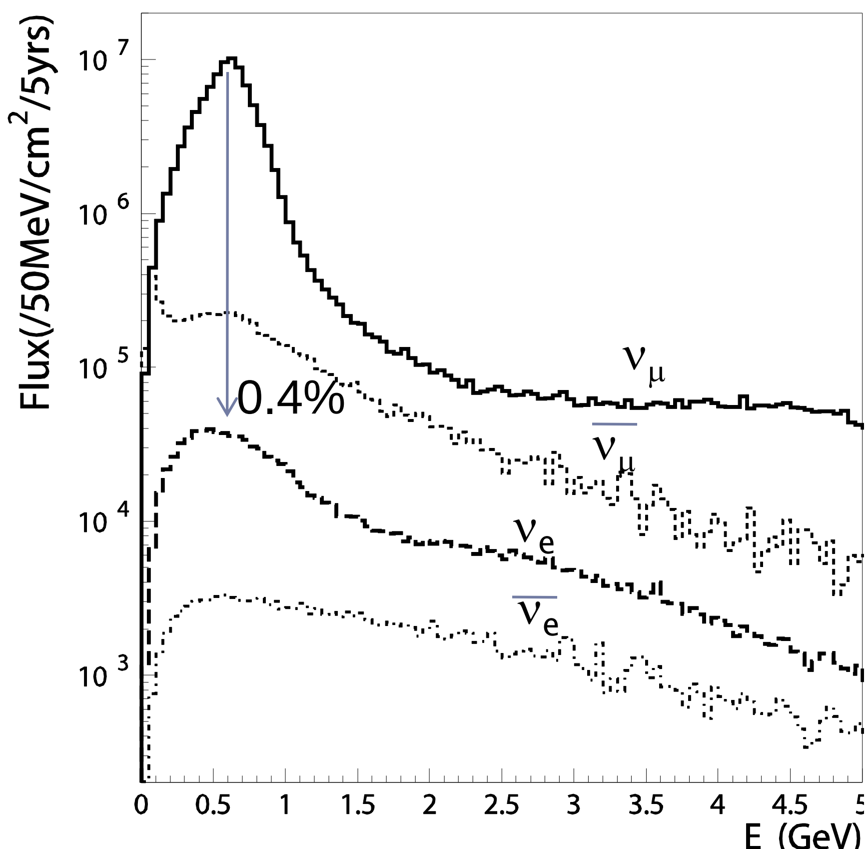


Pion decay kinematics

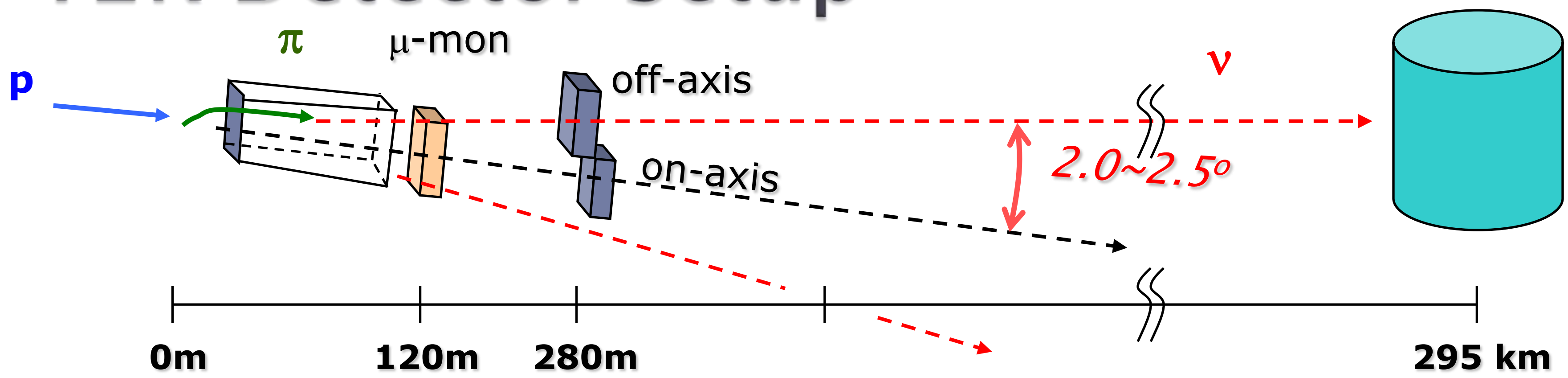


- **Off-axis beam (2.5deg)**
  - Intense narrow band beam
  - Tuned at osc max 0.7GeV
    (@L=295km, $\Delta m^2 = 2.5 \times 10^{-3} eV^2$)
  - 1600ν_μCC/22.5kt/year
    (no oscillation case)
- **Pure ν_μ beam**
  - ν_e contamination:
    ~ 0.4% at peak energy

Neutrino Flux at 295km



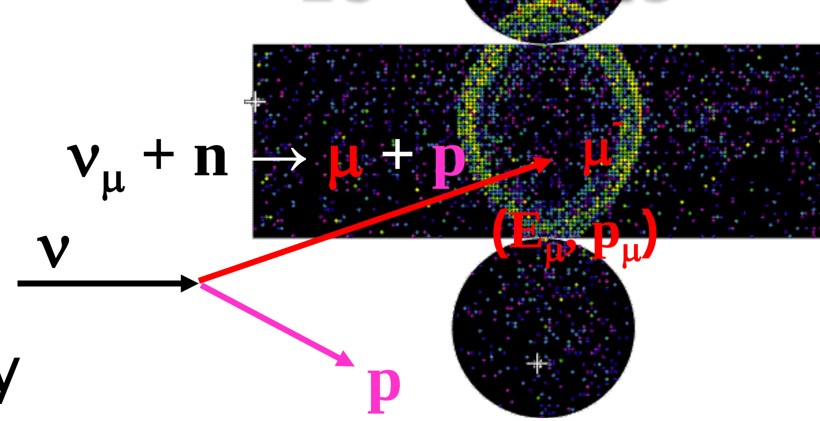
T2K Detector Setup



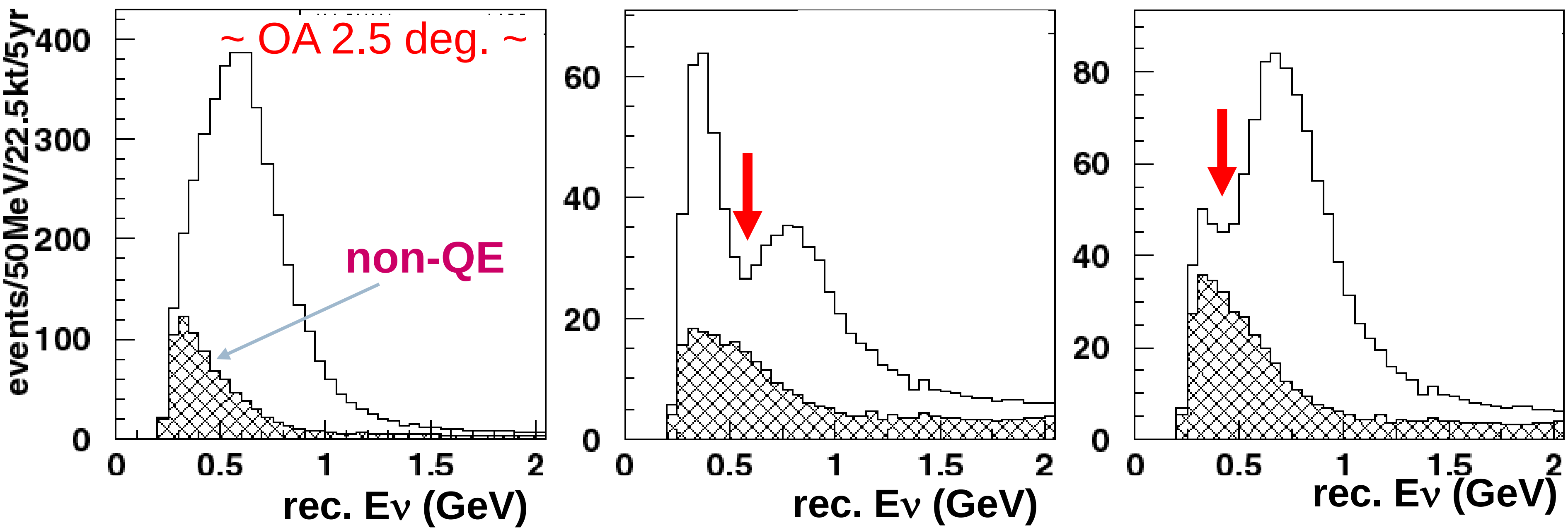
- **Muon monitors @ ~120m**
  - Fast (spill-by-spill) monitoring of neutrino beam direction/intensity
- **Near detectors @280m**
  - On-axis detectors
    - Monitor Neutrino Intensity and Direction (profile)
  - Off-axis detectors
    - Measure Flux/Spectrum/νe component/Cross-sections to understand Signal/Background systematics
- **Far detector @ 295km**
  - Super-Kamiokande (22.5kt FV)

Precision measurement of θ_{23}, Δm_{23}^2

- $\nu_\mu \rightarrow \nu_\tau$ disappearance
- Use Single μ-like ring events (ν_μ CC Quasi-Elastic enhanced sample) to reconstruct Neutrino Energy

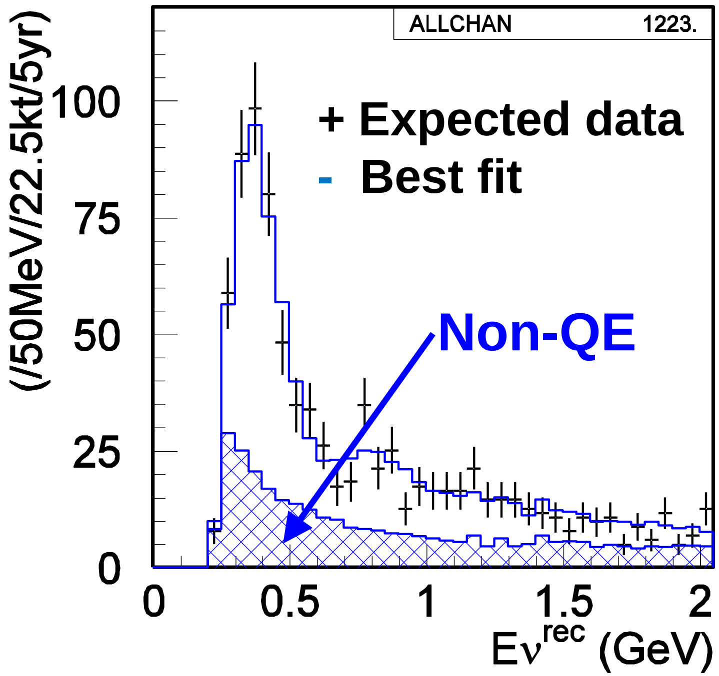


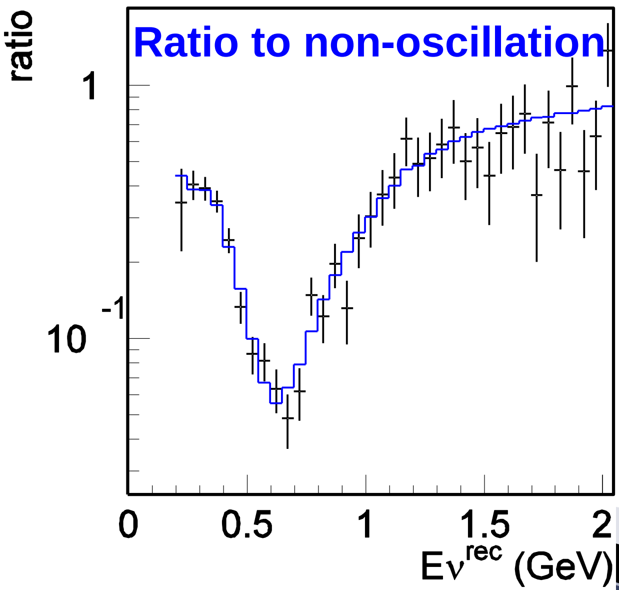
No oscillation | Δm^2= 2.5 x10^{-3} eV^2 | Δm^2= 2.0 x10^{-3} eV^2



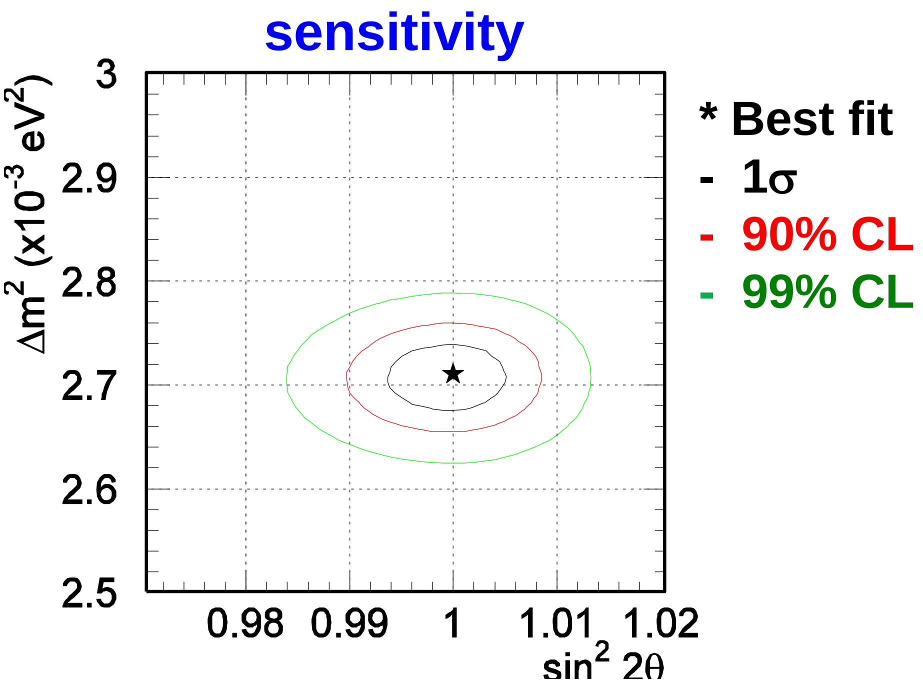
(assuming $\sin^2 2\theta_{23}$=1.0)

Oscillation Parameter fit





Input:
$\sin^2 2\theta_{23}$=1.00
Δm^2= 2.7 x10^{-3} eV^2



Target of T2K

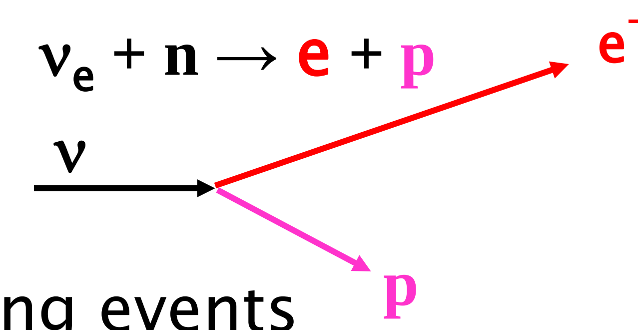
$\delta\Delta m^2$ ~ $1\times10^{-4} eV^2$

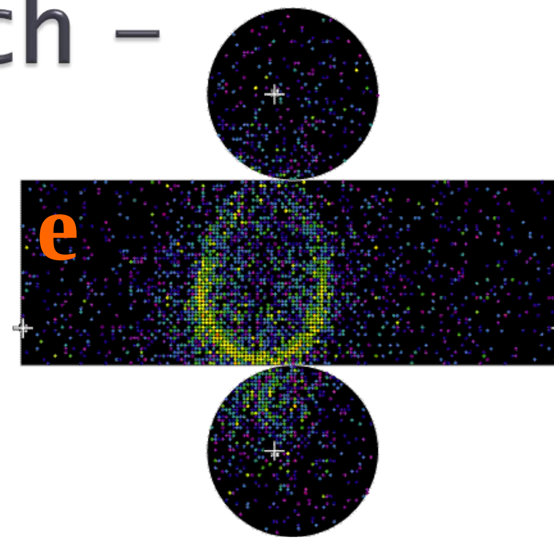
$\delta \sin^2 2\theta_{23}$~ 1%

θ_{13} measurement
– ν_e Appearance Search –

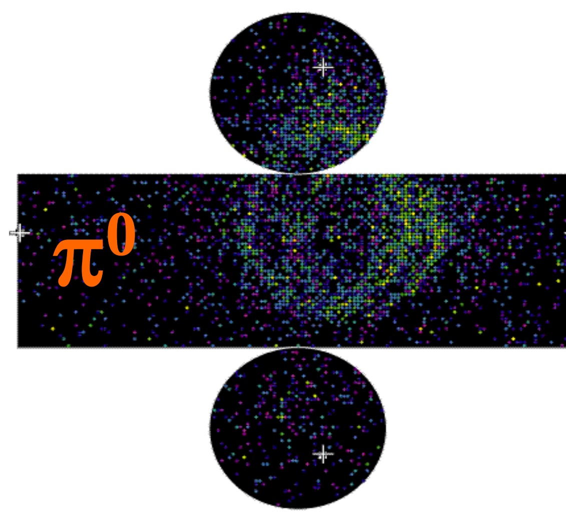
$$P_{\nu\mu\rightarrow\nu e} \approx \underbrace{\sin^2\theta_{23}}_{\sim 0.5} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\Delta m^2_{23} L / E_\nu\right)$$

$$\nu_e + n \rightarrow e + p$$





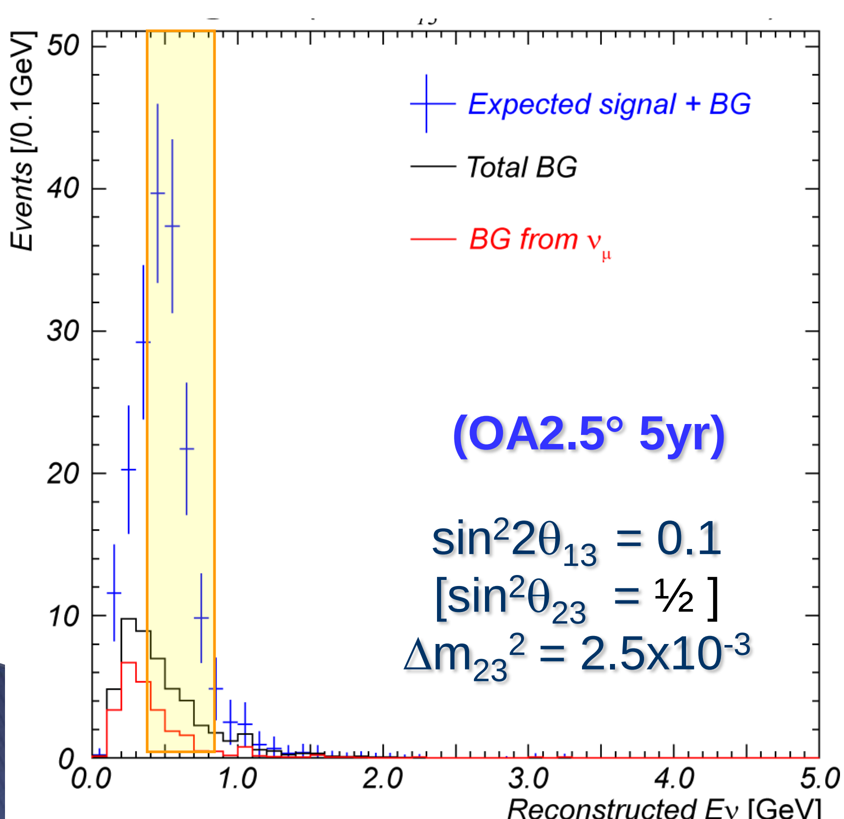
- Signal
  - single e–like ring events (ν_e CC Quasi–Elastic)
- Background
  - beam ν_e contamination (0.4% of ν_μ)
  - mis–reconstructed π^0 event

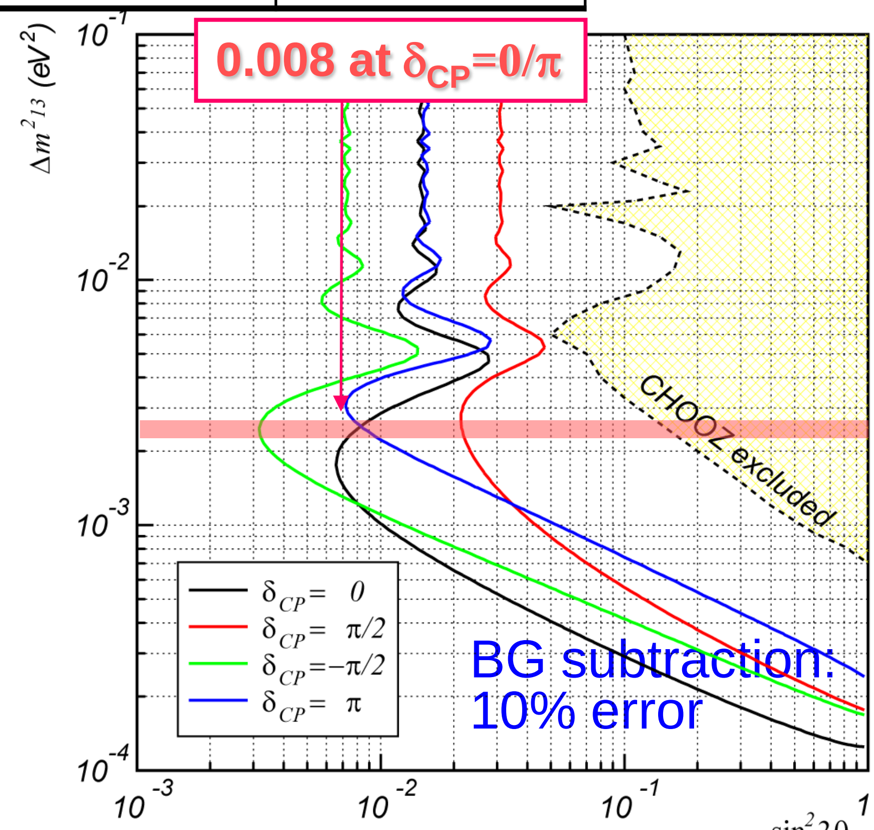


Sensitivity of ν_e appearance search

# of events in Eνrec=0.35~0.85 [GeV], 5yr

$\sin^2 2\theta_{13}$	Background in Super-K			Signal
	ν_μ	Beam ν_e	total	
0.1	10	13	23	103
0.01				10

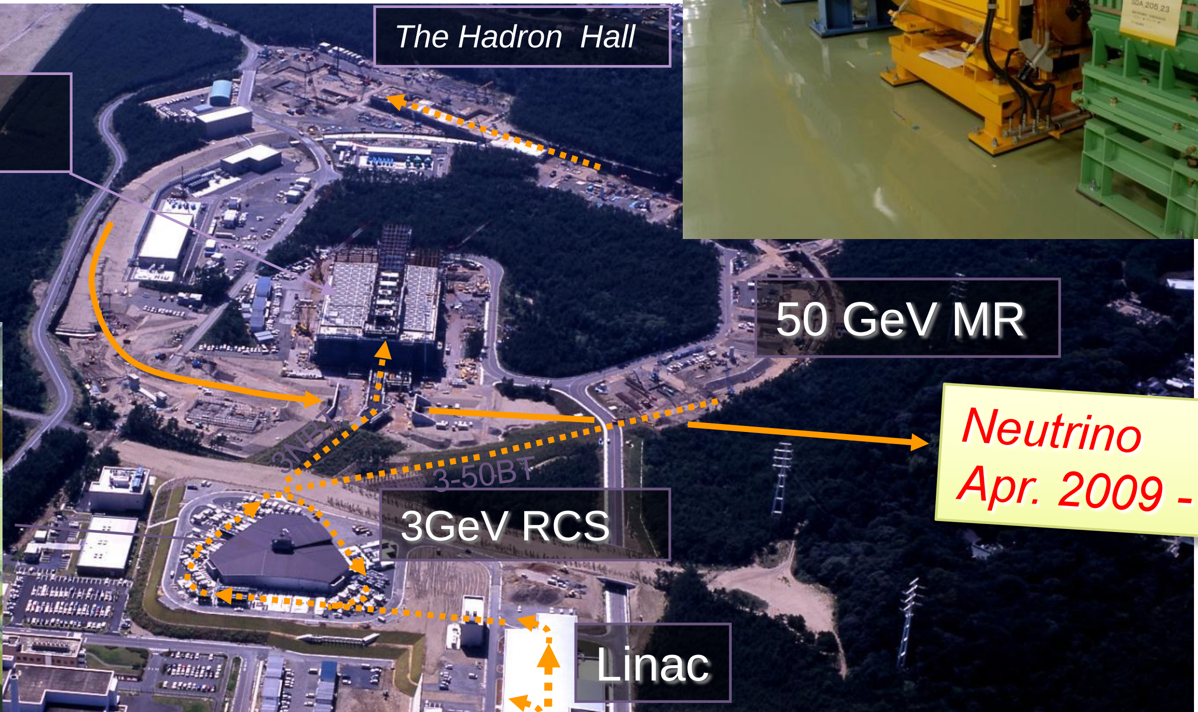




>10 times improvement from CHOOZ

Status of J-PARC

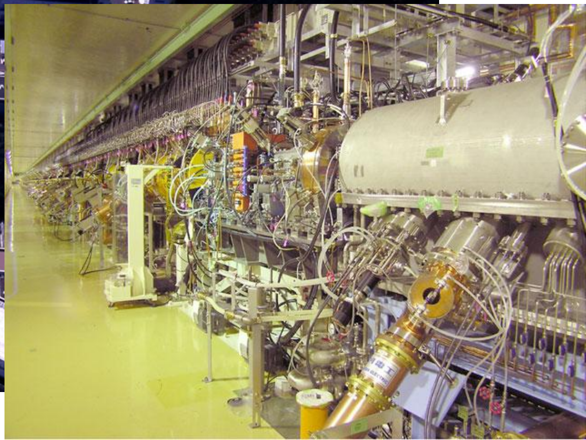
MR commissioning May, Jun, Dec~ in 2008



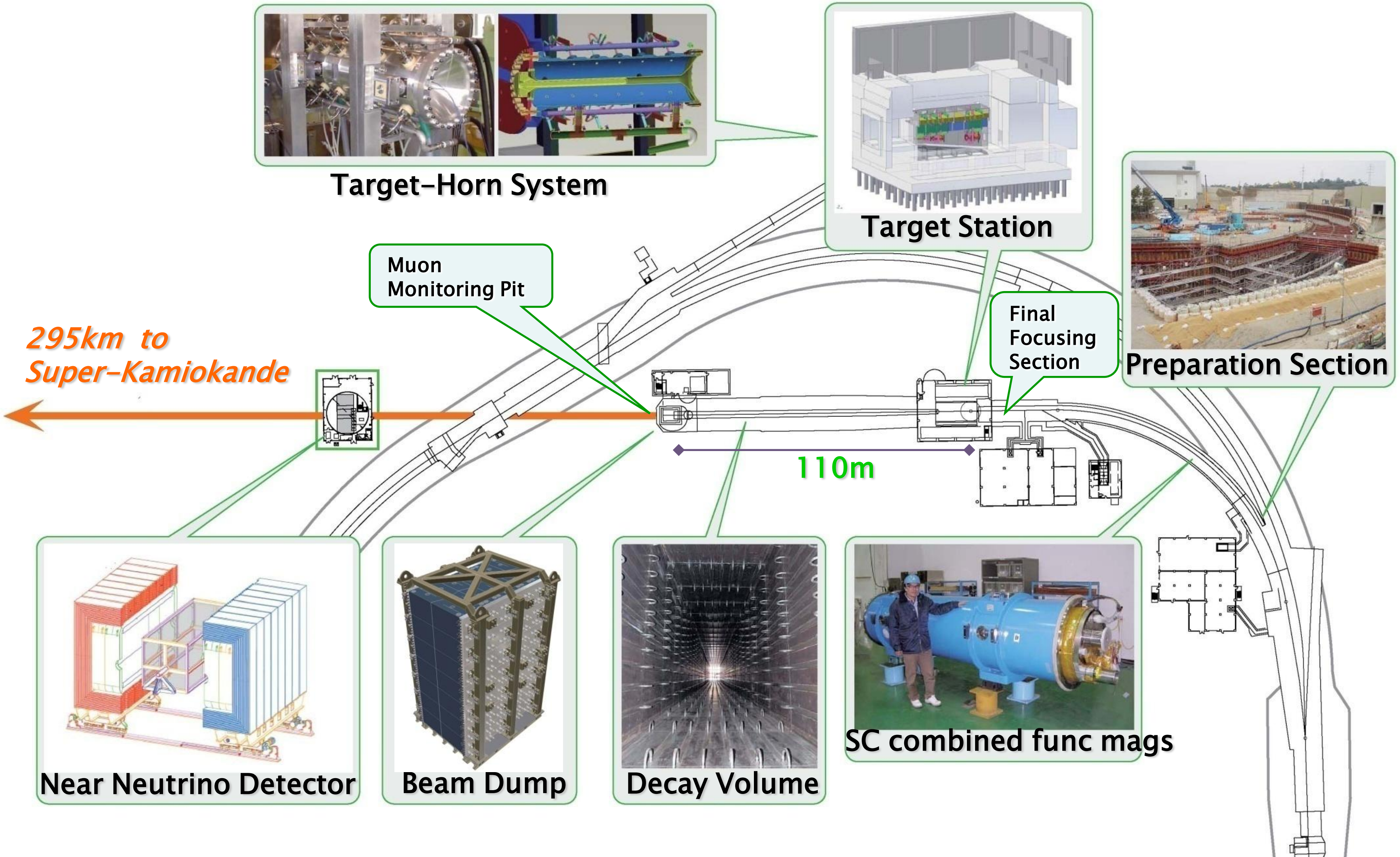
Neutrino Apr. 2009 -

3 GeV RCS beam commissioning succeeded in Nov. 2007

Linac succeeded in 181 MeV acceleration in Jan. 2007



Neutrino Facility in J-PARC



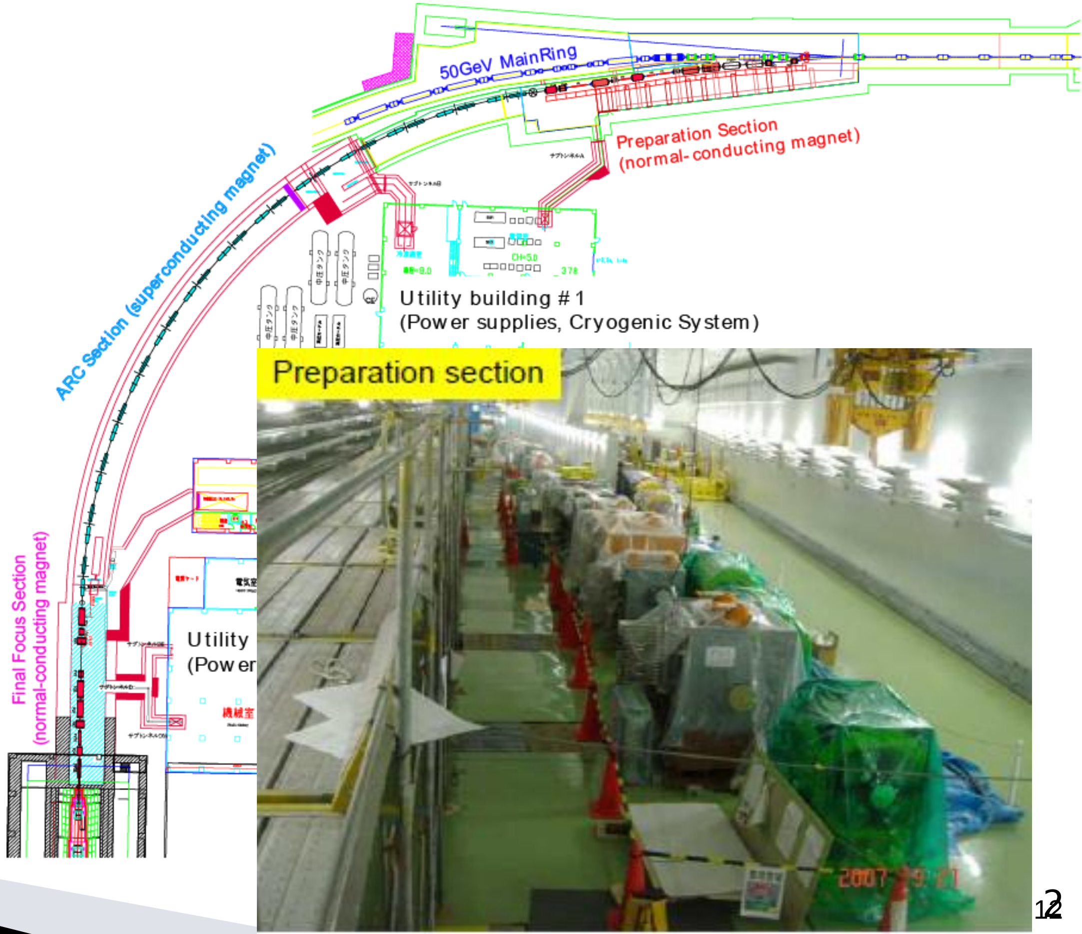
Construction: Apr. 2004 ~ Mar. 2009 (5yrs)

Primary proton beam line

- Superconducting Arc section
  - 28 combined function magnets
  - D2.6T,Q18.6T/m, L=3.3m
- Normal conducting Preparation section and Final focusing (FF) section
  - Installation in progress

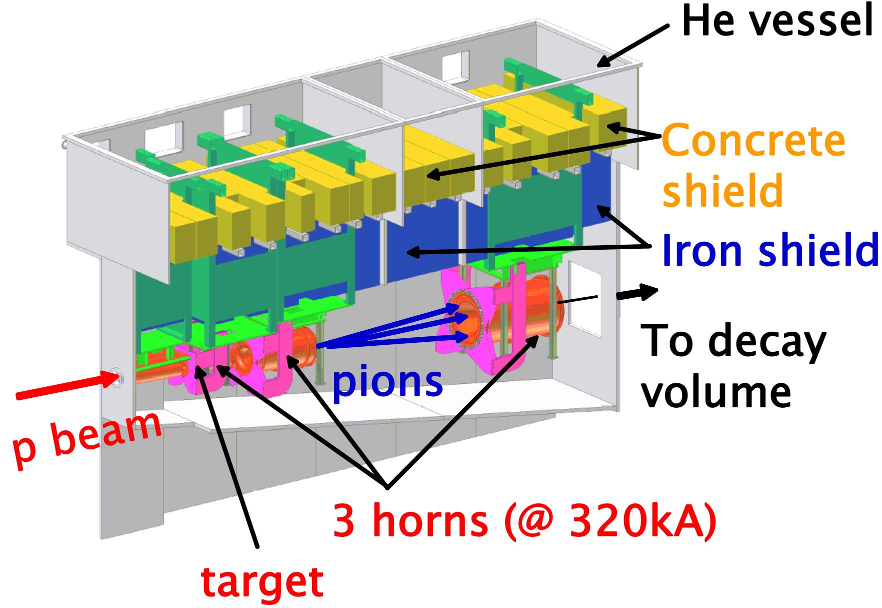
Tunnel completed (Dec. 2006)

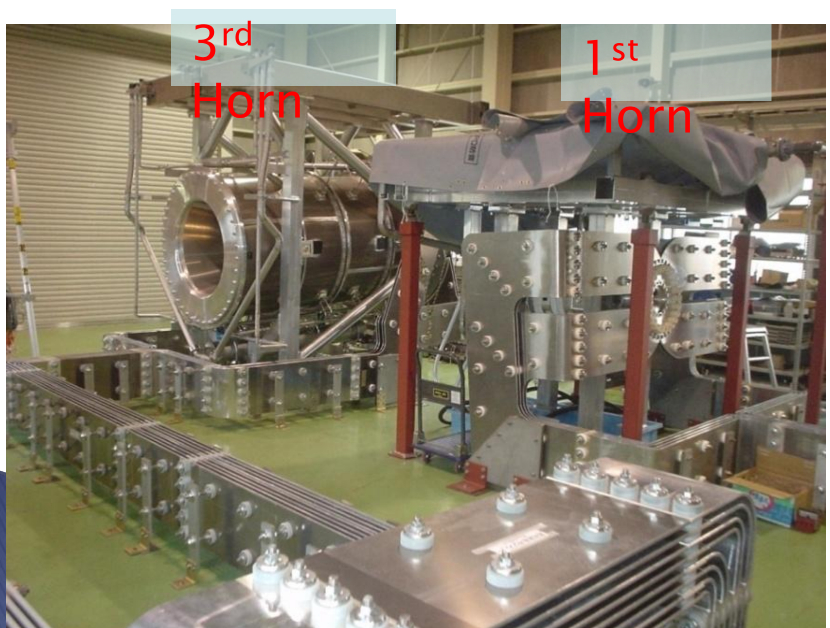
26(/28) mags delivered
11(/14) doubles installed



Target and horns

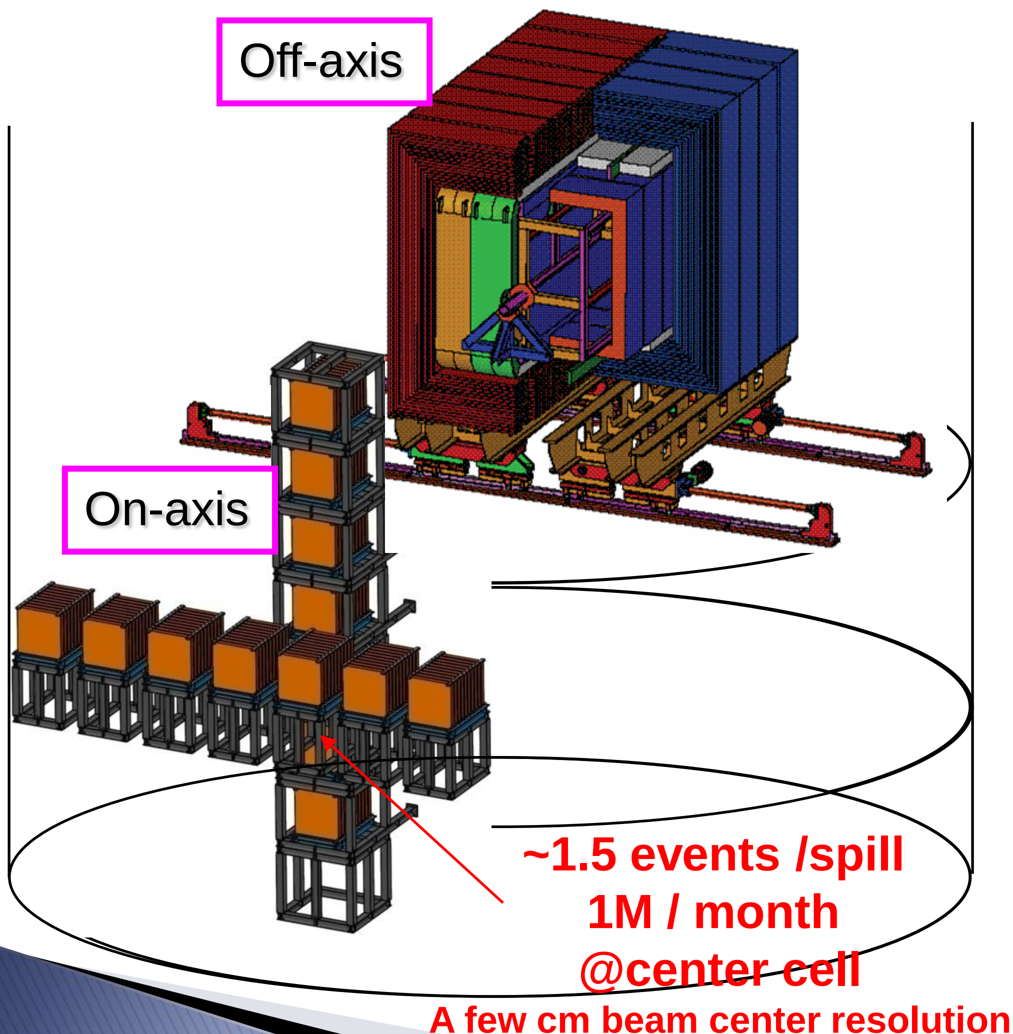
Graphite target (26mmϕx90cm)
Day-1 target delivered
Helium gas cooling test successful





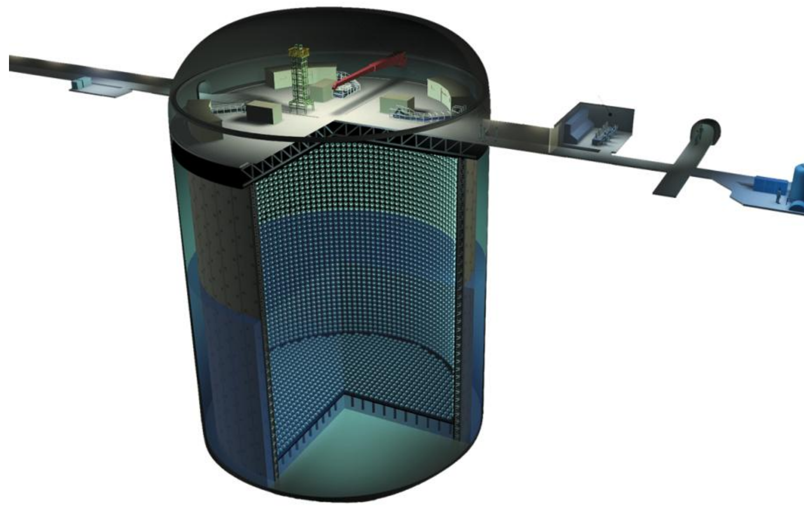
Long term test successful @ 320kA
Horn1,3 for Day-1 delivered

280m Near Detectors

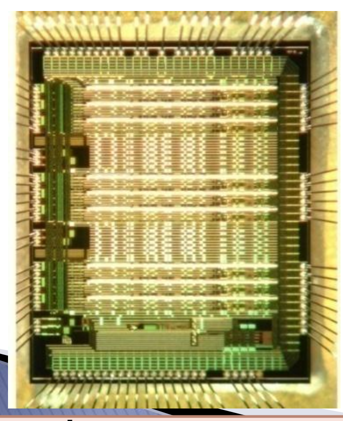


- On-Axis Detector INGRID
  - Monitor beam direction, flux and stability
  - Start operation from Apr. 2009
- Off-Axis Detectors
  - Measure Spectrum, Cross-sections, νe components
  - FGD, TPC, Ecal, …
  - In UA1 Magnet
    - Arrived in Apr., Under assembling in Apr – Jun 2008)
  - Operation Starts within 2009 (High Intensity Run)

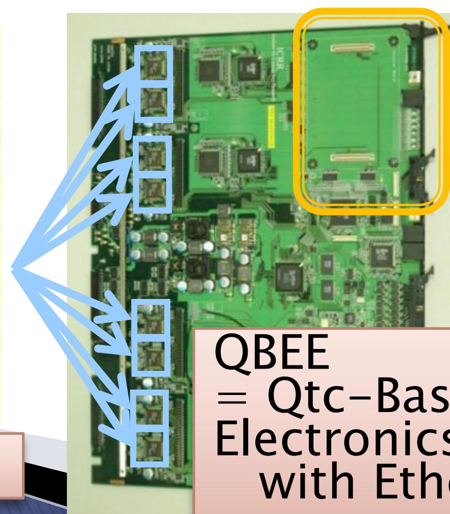
Far detector: Super-Kamiokande



- 50kton(Fid.Vol=22.5kton) Water Cherenkov detector
- L=295km from J-PARC
- Started operation in 1996
- Fully recovered in 2006 from damage @2001 accident.
- Electronics / Online Full Upgrade in Sep. 2008
  - Record ALL PMT hits



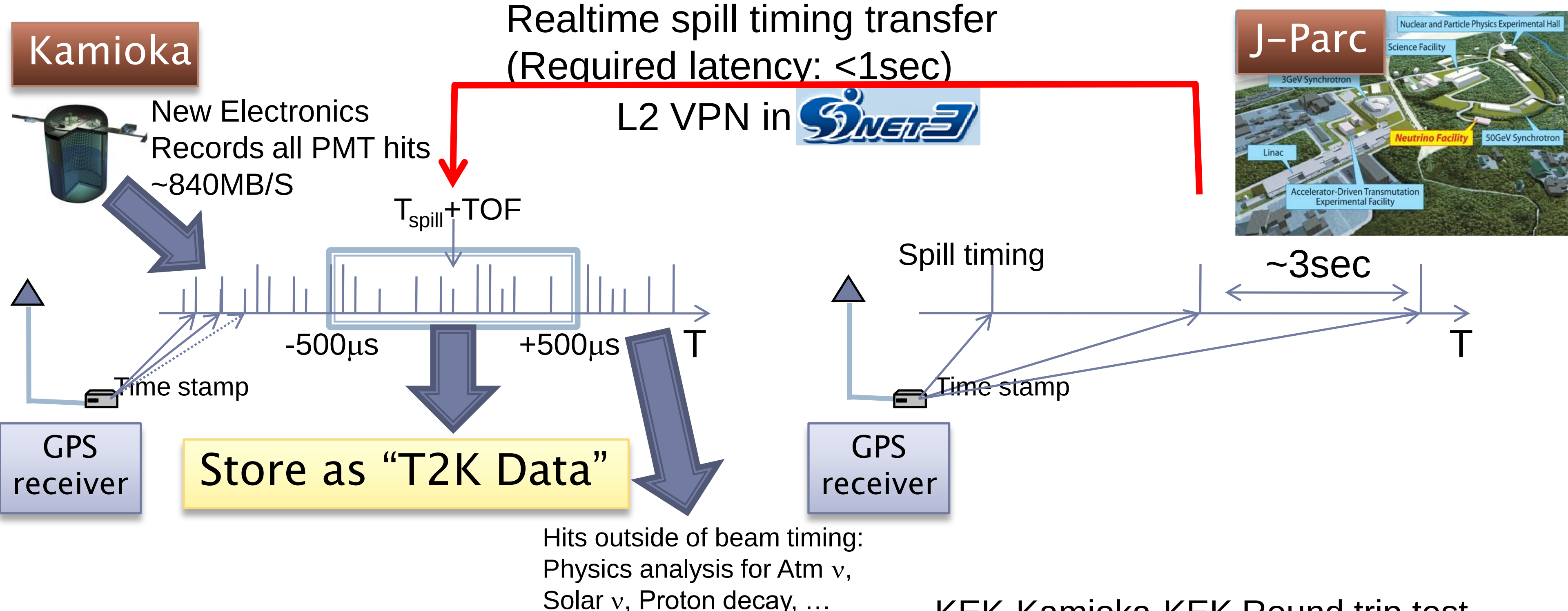
QTC chip



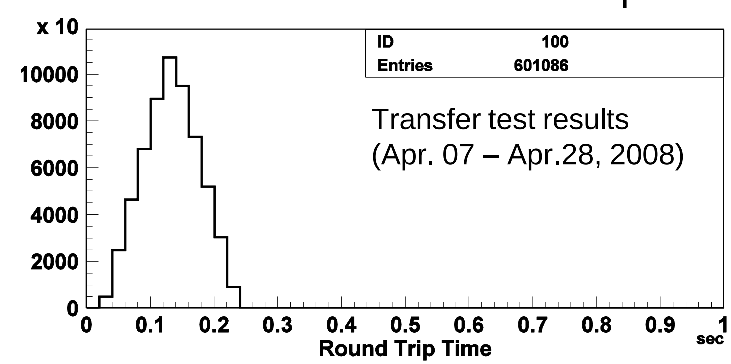
QBEE
= Qtc-Based Electronics with Ethernet

Ethernet card

T2K Events @ SK



KEK-Kamioka-KEK Round trip test



RTT < 0.25s.

- Long-term transfer test on Test VPN between KEK-Kamioka started on Mar. 2008

Summary of T2K

- T2K Tokai-Kamioka Long Baseline Neutrino Oscillation Experiment starts on Apr. 2009
- Primary Goal:
  - Explore ν_e appearance >10x of CHOOZ limit
  - Precise measurement of ν_μ disappearance
    - $\delta(\sin^2 2\theta_{23})\sim 0.01$, $\delta(\Delta m_{23}^2)\sim<1\times 10^{-4}$
- Start Plan:
  - Neutrino Beam: Fast extraction Starts on Apr. 2009
  - On-Axis detector: Starts on Apr. 2009
  - Off-Axis detector: Starts on Fall 2009
  - Far detector: Upgraded and ready by Apr. 2009

δCP measurement after discovery of θ_{13}

How can we measure δCP ?

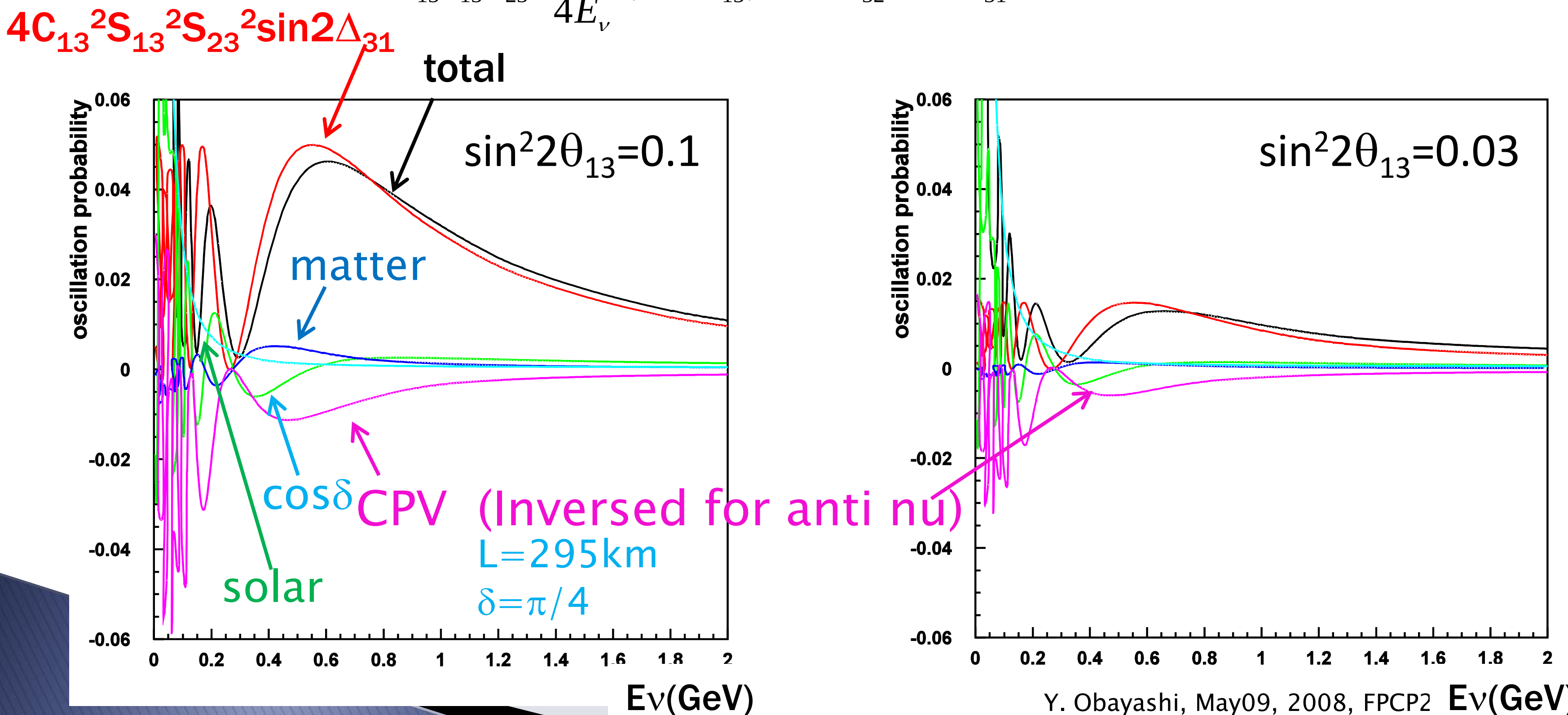
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \left(1 + \frac{2a}{\Delta m_{13}^2}(1-2S_{13}^2)\right) \cdot \sin^2\Delta_{31}$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$ CP conserving

$$\mp 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \underline{\sin\delta} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$ CPV

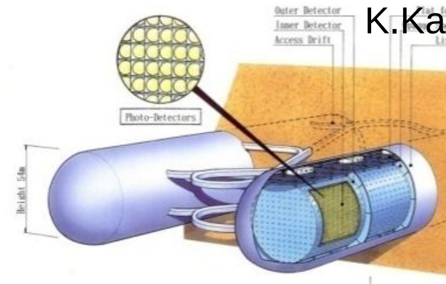
$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \underline{\cos\delta}) \cdot \sin^2\Delta_{21}$$ solar ν

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1-2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$ matter effect



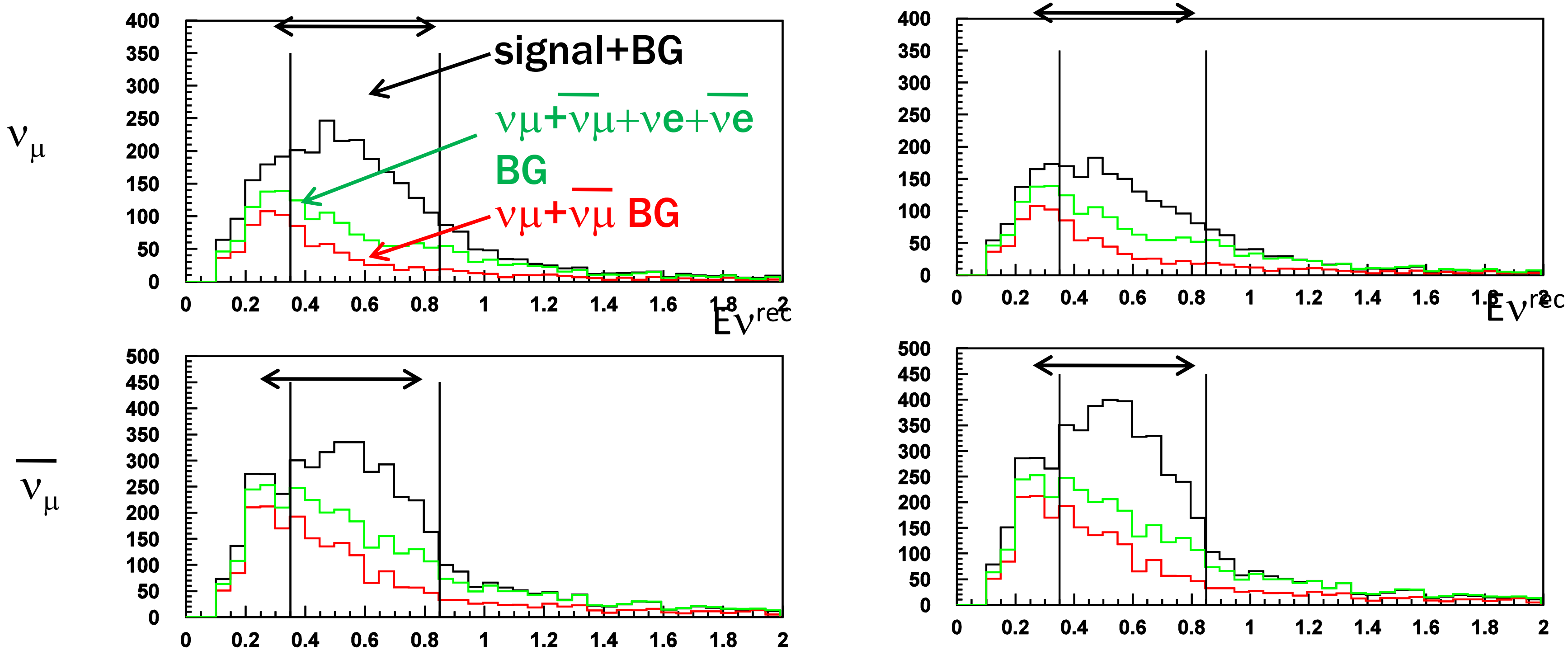
an example of **Expected Signals**

K.Kaneyuki NP08



- Assume large statistics here by <u>Gigantic detector</u> (540kt WC) and <u>Beam power</u> upgrade(1.7MW)

$\delta=0$ $\delta=\pi/2$ $(\sin^2 2\theta_{13}=0.03)$

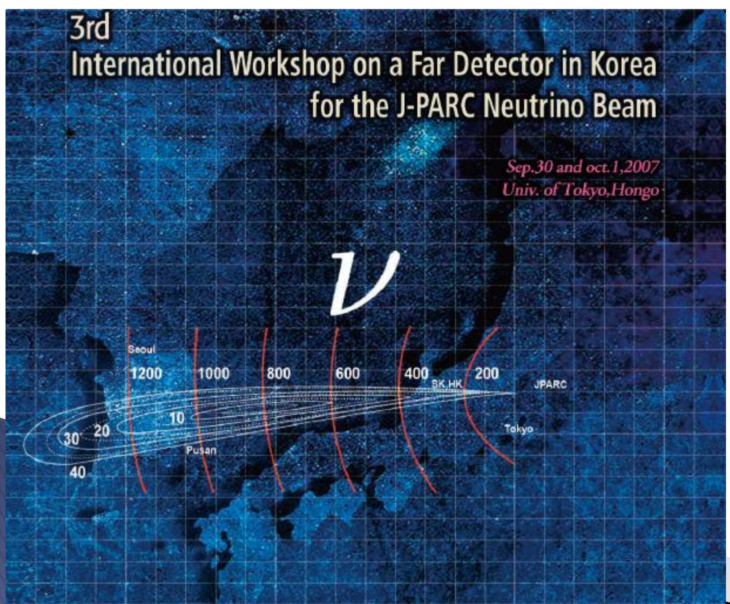


	$\nu\mu \rightarrow \nu e$ signal		backgroud			
	$\delta=0$	$\delta=\pi/2$	ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$
ν_μ 2.2yr	1049	579	354	26	379	10
$\overline{\nu}_\mu$ 7.8yr	1050	1493	443	610	241	415

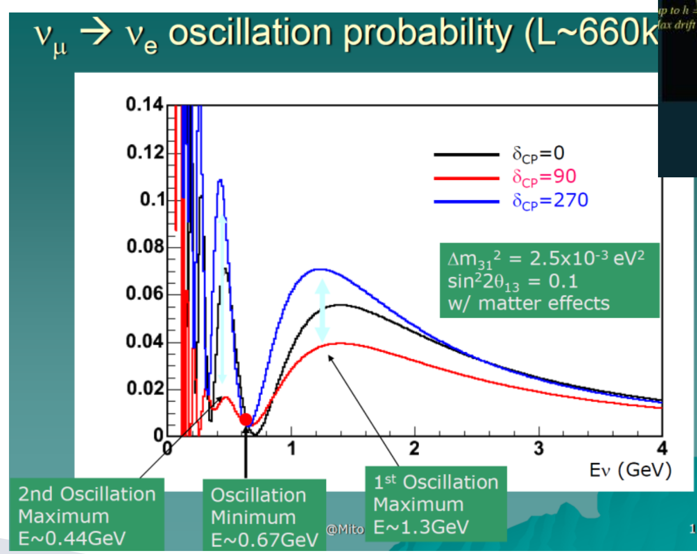
Neutrino goes NOT Only to Kamioka

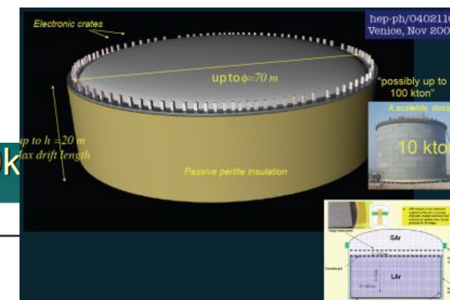
>Mton Water Ch. In the Sea?
Y.Suzuki @ NNN07

Additional Water Ch. @ Korea?
"T2KK"



100kt Liq. Ar TPC Okinoshima?
T. Maruyama @ NP08





Summary

- T2K Tokai-Kamioka Long Baseline Neutrino Oscillation Experiment starts on Apr. 2009
- Primary Goal:
  - Explore ν_e appearance >10x of CHOOZ limit
  - Precise measurement of ν_μ disappearance
    - $\delta(\sin^2 2\theta_{23}) \sim 0.01$, $\delta(\Delta m_{23}{}^2) \sim < 1 \times 10^{-4}$
- Start Plan:
  - Neutrino Beam: Fast extraction Starts on Apr. 2009
  - On-Axis detector: Starts on Apr. 2009
  - Off-Axis detector: Starts on Fall 2009
  - Far detector: Upgraded and ready by Apr. 2009
- After νe appearance discovery, CP physics in neutrino is very much Interesting

Suppliments

Physics Introduction

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

ν_α: Weak eigenstates, $\alpha=e,\mu,\tau$

ν_i: Mass eigenstates $\Delta m_{ij}^2 = m_i^2 - m_j^2$

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

NMS Matrix

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

Neutrino Oscillation Probability

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta(t)|\nu_\alpha(0)\rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)\cdot\sin^2\phi_{ij} \mp 2\sum_{i>j}\mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)\cdot\sin 2\phi_{ij}$$

$$\phi_{ij} = \Delta m_{ij}^2 L / 4E_\nu$$

Two neutrino case when $\Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2$

$\nu\mu$ disappearance probability

$$P_{\nu\mu\to\nu x} \approx 1 - \cos^4\theta_{13}\cdot\sin^2 2\theta_{23}\cdot\sin^2\left(1.27\Delta m_{23}^2 L/E_\nu\right)$$

νe appearance probability in $\nu\mu$ beam

$$P_{\nu\mu\to\nu e} \approx \sin^2\theta_{23}\cdot\sin^2 2\theta_{13}\cdot\sin^2\left(1.27\Delta m_{23}^2 L/E_\nu\right)$$

Current Knowledge

Cosmic ν,
Accelerator ν
Reactor ν

- $\Delta m_{23}^2 \sim \Delta m_{13}^2 = (2 - 3) \times 10^{-3} eV^2$
  $\sin^2 2\theta_{23} > 0.92$ (SK atm ν, K2K, MINOS)
- $\Delta m_{12}^2 \sim 8 \times 10^{-5}\ eV^2$
  $\sin^2 2\theta_{12} \sim 0.86$ (KamLAND + solar ν (SK + SNO))
- $\sin^2 2\theta_{13} < 0.15 @ \Delta m^2 = 2.5 \times 10^{-3}\ eV^2$ (CHOOZ / Palo Verde)
  - < 0.26 (0.13x2) at $\Delta m^2 = 2.8 \times 10^{-3}\ eV^2$ (K2K)
- δ_{CP} : UNKNOWN

$$P_{\nu\alpha \to \nu\beta} \approx \sin^2 2\theta_{\alpha\beta} \cdot \sin^2\left(1.27 \Delta m^2_{\alpha\beta} L / E_\nu\right)$$

The derived ranges for the six parameters at 1σ (3σ) are:

$$\Delta m^2_{21} = 7.67 ^{+0.22}_{-0.21} \left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2,$$

$$\Delta m^2_{31} = \begin{cases} -2.37 \pm 0.15 \left(^{+0.43}_{-0.46}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(inverted hierarchy)}, \\ +2.46 \pm 0.15 \left(^{+0.47}_{-0.42}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(normal hierarchy)}, \end{cases}$$

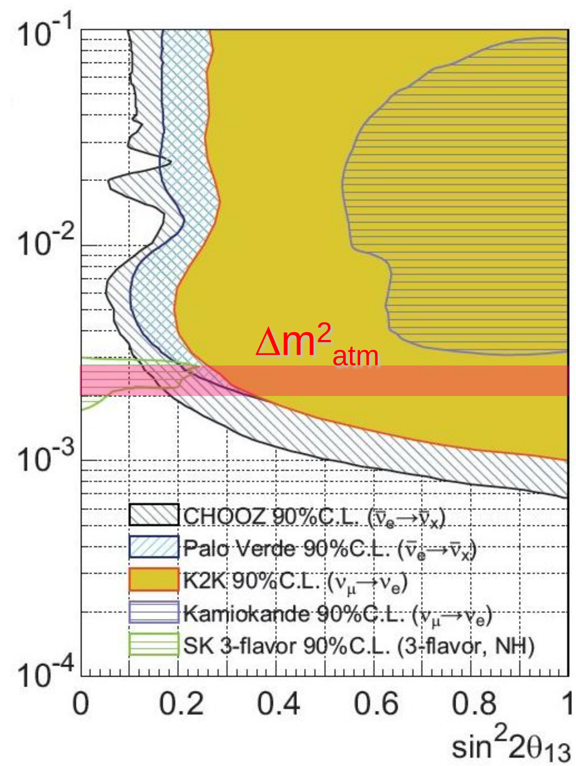
$$\theta_{12} = 34.5 \pm 1.4 \left(^{+4.8}_{-4.0}\right),$$

$$\theta_{23} = 42.3 ^{+5.1}_{-3.3} \left(^{+11.3}_{-7.7}\right),$$

$$\theta_{13} = 0.0 ^{+7.9}_{-0.0} \left(^{+12.9}_{-0.0}\right),$$

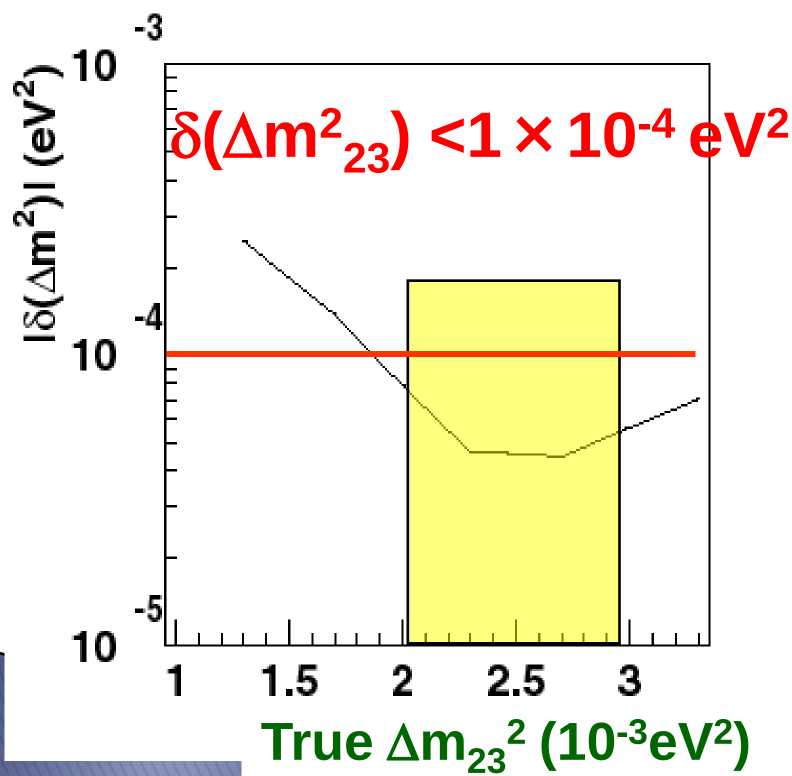
$$\delta_{CP} \in [0, 360].$$

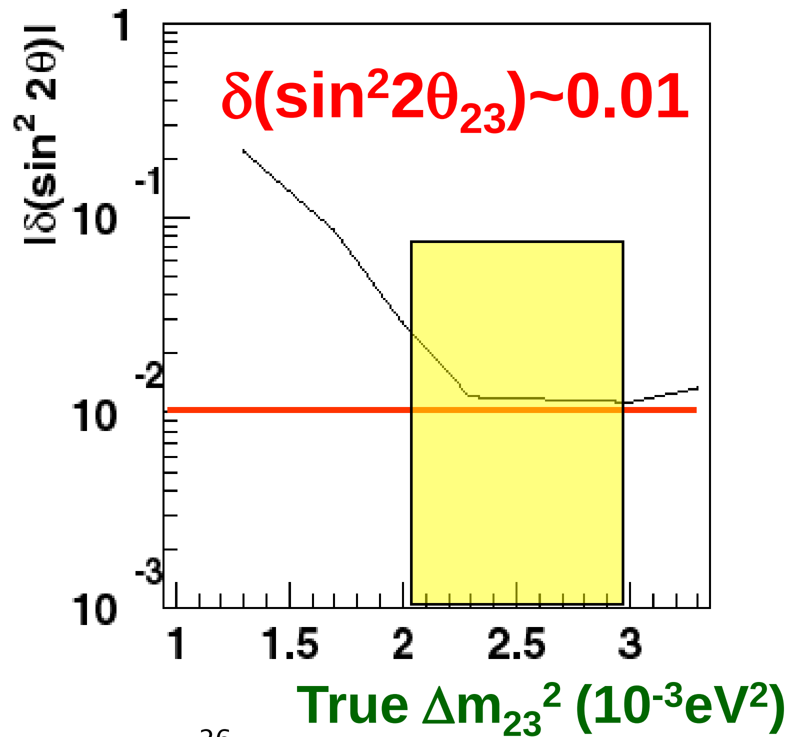
M.C. Gonzalez-Garcia, M. Maltoni / Physics Reports 460 (2008) 1–129



Sensitivity with Systematics

Flux Normalization	(5%)
Non-qe/qe ratio of interaction σ	(5%)
Energy scale of Far detector	(2%)
Spectrum shape	(20%)
Spectrum width	(5%)

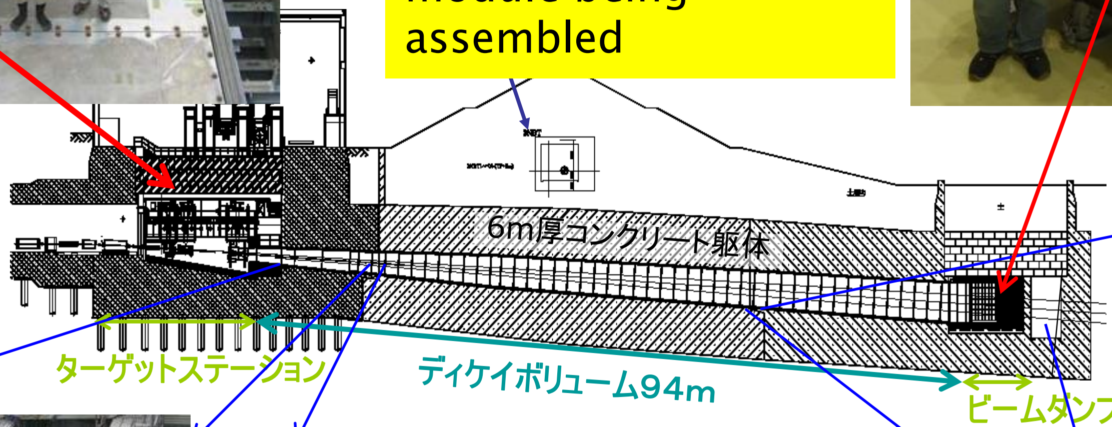




Secondary beam line

He vessel (470t,1000m3) completed, passed vac test in Nov. 2007

Beam dump graphite module being assembled

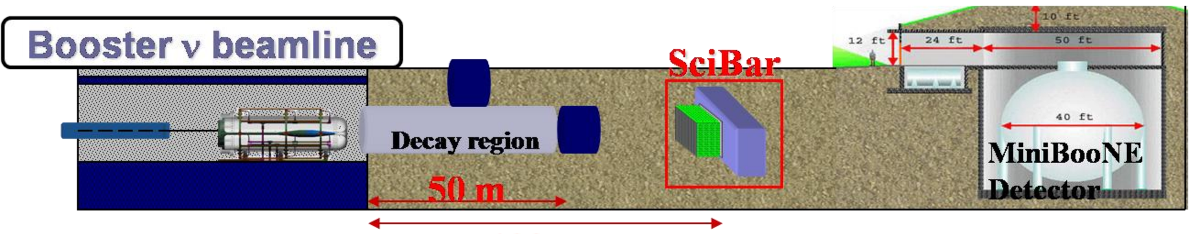


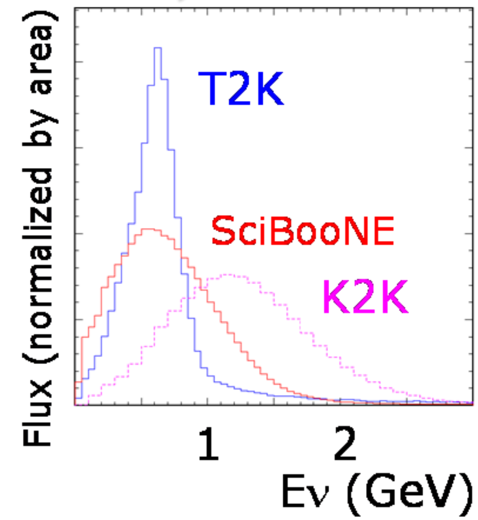
DV under 3NBT installed in

Mar. 2008

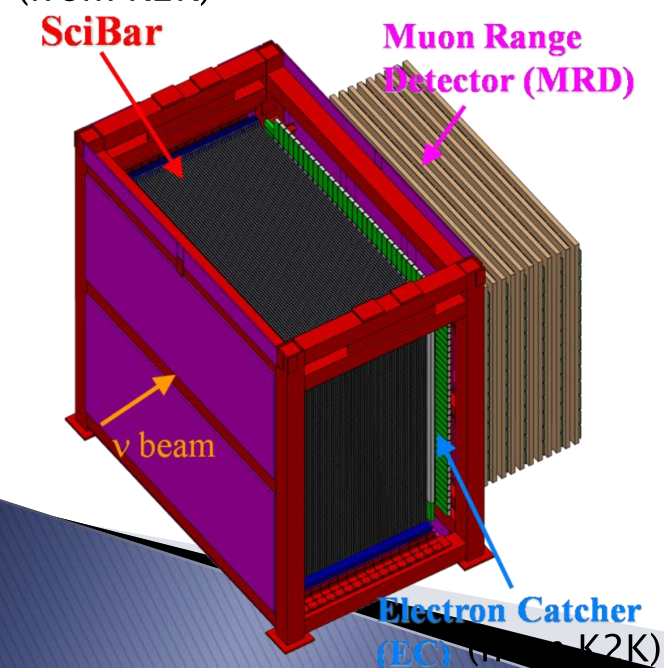
SciBooNE @ FNAL (Jun2007~)

- $\nu\mu$, $\bar{\nu}\mu$ cross section at sub GeV (~T2K)
- Kyoto/TIT/ICRR/KEK from Japan
- Total collected POT: 1. 46E20
  - ν: 9.2E19 (goal: 1E20)
  - $\bar{\nu}$: 5.4E19 (goal: 1E20)

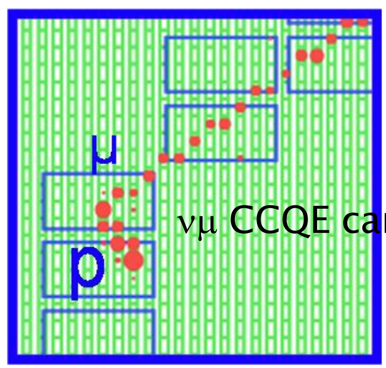


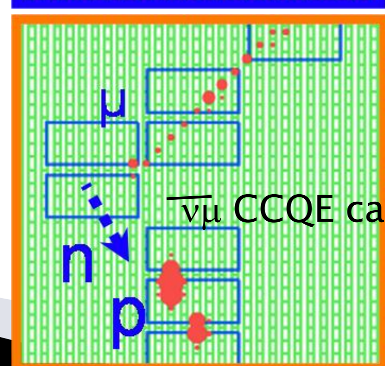


(from K2K)

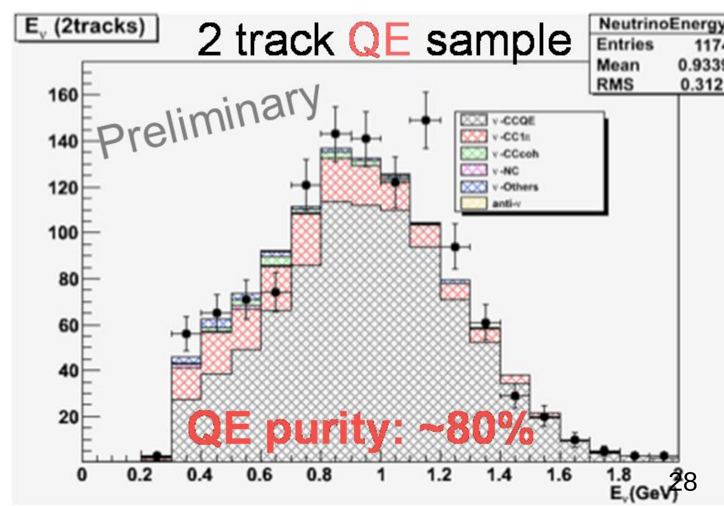


(from K2K)





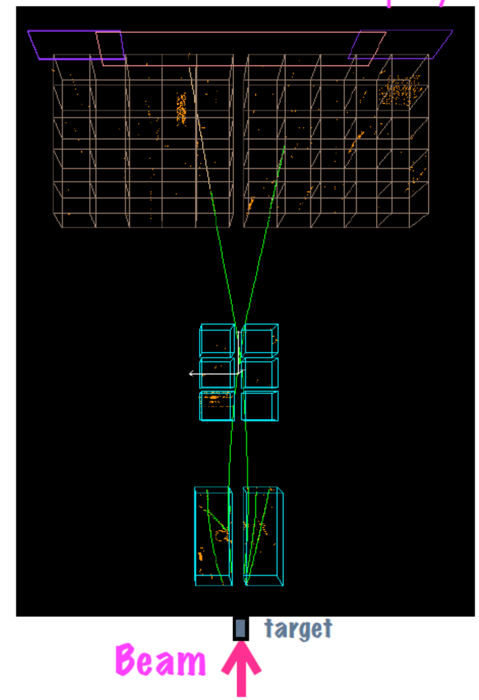
Intensive analysis in progres on various modes

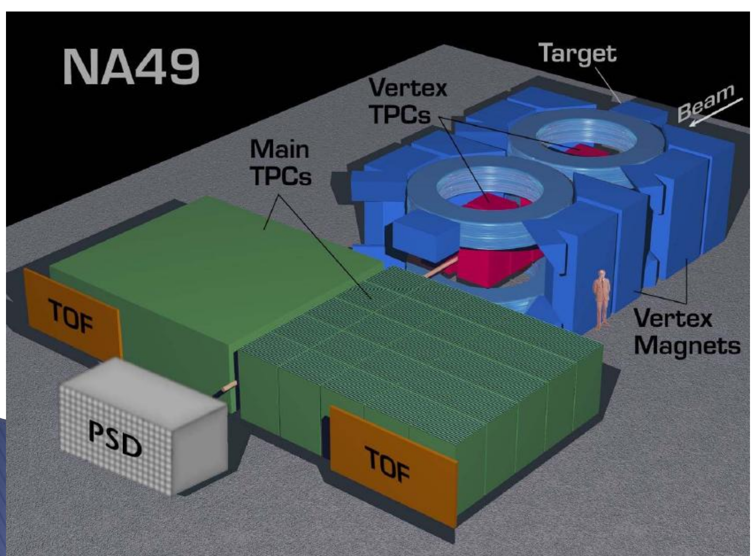


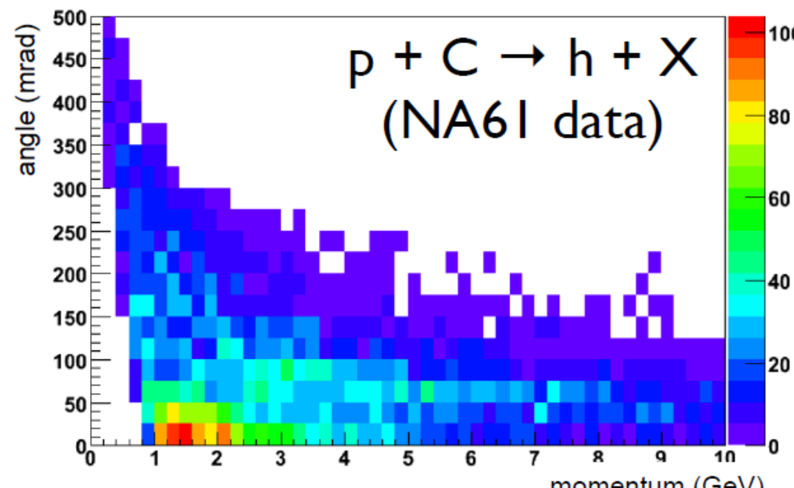
CERN-SPS NA61 (SHINE) experiment

- Measure π/K prod. from Graphite target to predict
  - Near and far energy spectra (<2~3%)
  - Near to far spectrum extrapolation (<2~3%)
  - ν_e contami. (from K, μ) (<2~3%)
- **First data taking in Oct., 2007 (1month)**
  - Beam: 30GeV proton
  - Thin target (2cm[t] 4%int):~ 500k int.
  - Replica target (90cm, 80%int): ~180k int.
- Measurements in 2008 planned

Event display

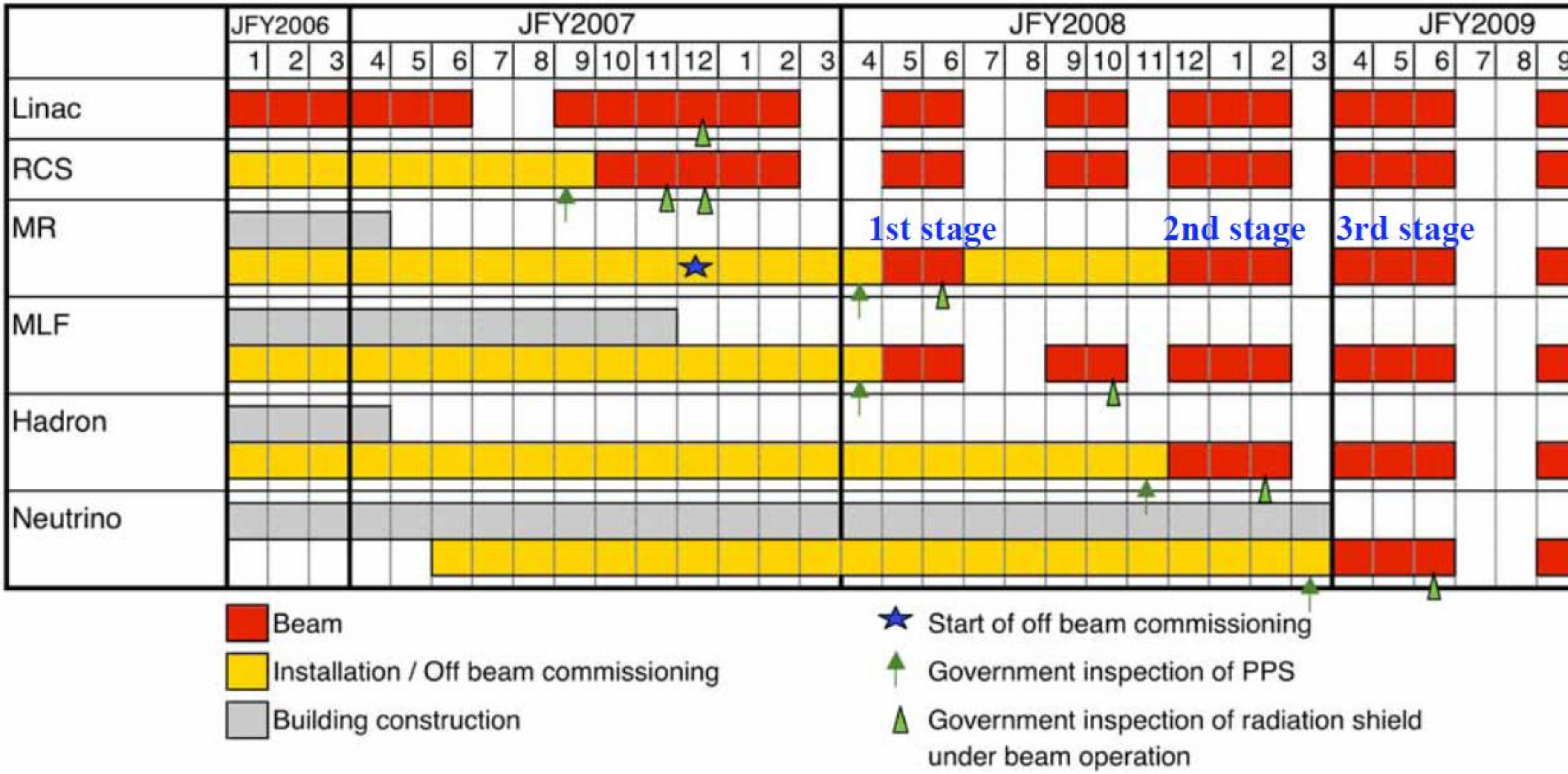






First look of data
(PID, acceptance not corrected)

Schedule of beam commissioning



MR schedule

Dec. 2007-April 2008 :Off beam commissioning

March-April 2008: Modification of the PPS (to add the interlock system of MR&MLF) and government inspection.

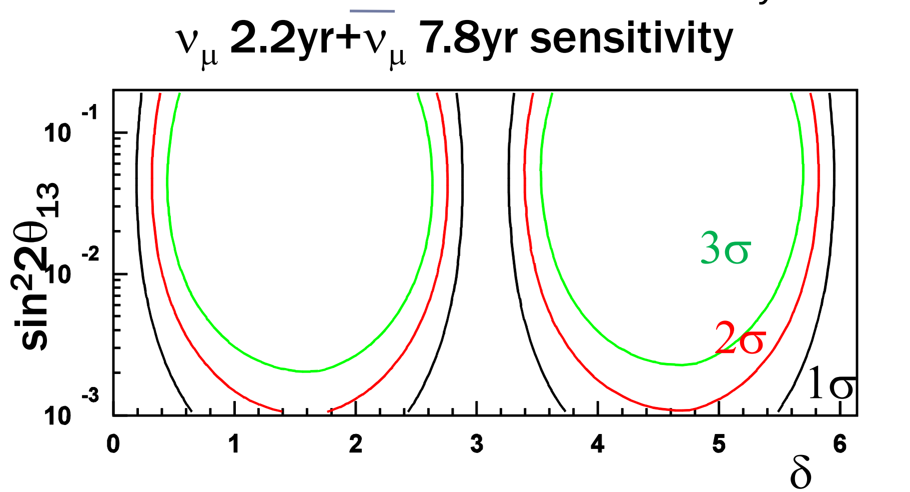
May 2008: MR (and MLF)beam commissioning starts.

July -Nov. 2008 : Installation of slow extraction devices, some fast extraction devices and neutrino beamline components.

Expected Sensitivity

- Assumed systematics
  - signal efficiency 5%
  - $\nu\mu$, $\overline{\nu\mu}$ BG 5%
  - beam νe, $\overline{\nu e}$ BG 5%
  - $\overline{\nu\mu}$ / $\nu\mu$ 5%
- These errors are still challenging but are essentially needed to be small for the CP measurement.

K.Kaneyuki NP08



Intensity upgrade plan of the first three years

			JFY 2007								JFY 2008												JFY2009											
			8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
LINAC	Output power <for RCS	kW		5.4<0.25>								5.4<0.6>				5.4<1.2			6				15					<18>						
	Peak current	mA		5-25																														
	Pulse width	nsec		50-100								50-250																						
	Beam Rep.	pps		single - 25								single - 25																						
RCS (MLF)	Output power	kW		4								4				4			100				250					(280)						
	Typical Beam Rep.	pps		single - 25								single - 2				single - 25																		
	No. of Bunches			1 - 2								1 - 2				1- 2			1- 2				1- 2					2						
	Particles /bunch for MLF			4.2E11								4.2E11				8.5E11			4.2E12				1.1E13					1.2E13						
	Particles /bunch for MR																		(4.2E11)				(4.2E11)											
	Particles /ring for MLF																		8.3E12				2.1E13											
	Particles /ring for MR																		(8.3E11)				(4.2E11)											
MR	Output power	kW										0.12							1.2				3.6					100						
	Energy	GeV										3							30															
	Typical Beam Rep.	pps										0.3																0.3 - 0.5						
	No. of Bunches											1 - 2							1 - 2				6					6						
	Particles /bunch											4.2E11							4.2E11				4.2E11					1.2E13						
	Particles /ring											8.3E11							8.3E11				2.5E12					7.2E13						
HD	Output power	kW																	1.2															
	Energy	GeV																	30															
	Particles /burst																		8.3E11															
NU	Output power	kW																					3.6					100						
	Energy	GeV																					30											
	Particles /burst																						2.5E12					7.2E13						

- Requirement from T2K: 2.0E20 protons on the ν target by the 2010 summer shutdown.
- Guideline :Beam loss at each extraction point < 25 -100 W to keep residual radiation level < 1mSv/h.

T2K Discovery Potential on $\nu_\mu \rightarrow \nu_e$ as a Function of Integrated Power