T2K

(Tokai to Kamioka Neutrino Oscillation Experiment)

1. The T2K collaboration
2. Main physics goals
3. Experimental setup and construction status
4. Sensitivities
5. Financial situation (if necessary)

J-PARC Program Advisory Committee Meeting

Koichiro Nishikawa
KEK

July 1, 2006

T2K Collaboration

- 11 Countries (number of members)
  - –Canada(24), France(8), Italy(11), Japan(46), Korea(9), Poland(1), Russia(8), Spain(12), Switzerland(3), UK(25), USA(42)
  - –58 Institutes, 189 Ph.D. members
- K2K, Super Kamiokande, SNO, CHOOZ, IMB, ...ILC

Non-zero mass of neutrinos !

What kind of physics can have comparable impact?

Physics esp. history of neutrino studies show *full of surprises*

(Kamiokande for Kamioka Nucleon decay Experiment !)

1. Look for un-expected by precision measurements of oscillation

- 3 generation *(paradigm)*
  - Consistency of Δm^2 in disappearance and appearance processes
  - Sub-process of flavor changing process (in addition to osc.)
  - Oscillation pattern ….

2. ν_e appearance

- The last mixing to be found
  - θ_{23}~45° θ_{12}~34°, Is θ_{13} special ?
- Determine future direction of neutrino experiment
  - Lead to only practical test of CPV in leptonic process
  - Complex phase in mixing in light neutrinos → leptogenesis?

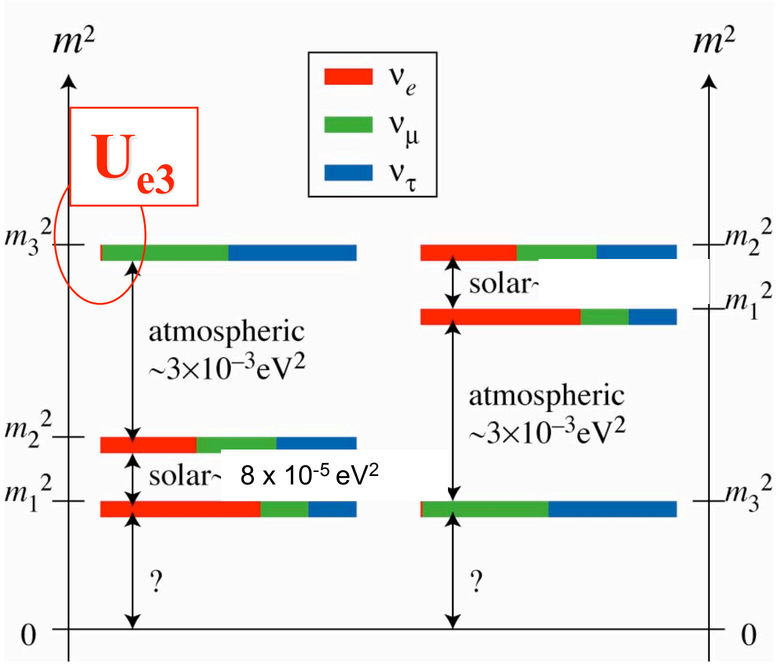
Emphasis on lepton ID and the determination of neutrino energy E_{ν}

Bread & butter physics in next generation accelerator experiments

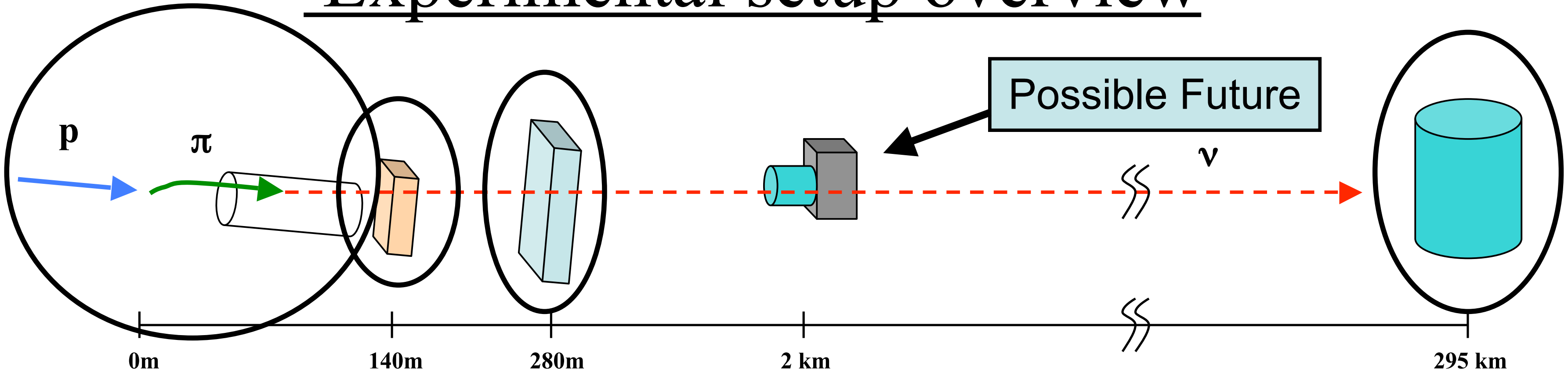
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{pmatrix}\nu_1(m_1)\\ \nu_2(m_2)\\ \nu_3(m_3)\end{pmatrix}$$

[illegible]

- Small ν_e component in ν3 U_{e3} =0 ?
  - θ_{23}~45° θ_{13}~34°,
  - Is θ_{13} much smaller or a little smaller? (test to 3°)
- ν3 consists of ν_μ, ν_τ = 50:50 ?
  - Another symmetry?
- Are neutrino mass and charged lepton mass ordering same or inverted
  - Is the largest component in νe : ν1 the lightest ?
- Possible differentiation between particle and anti-particle



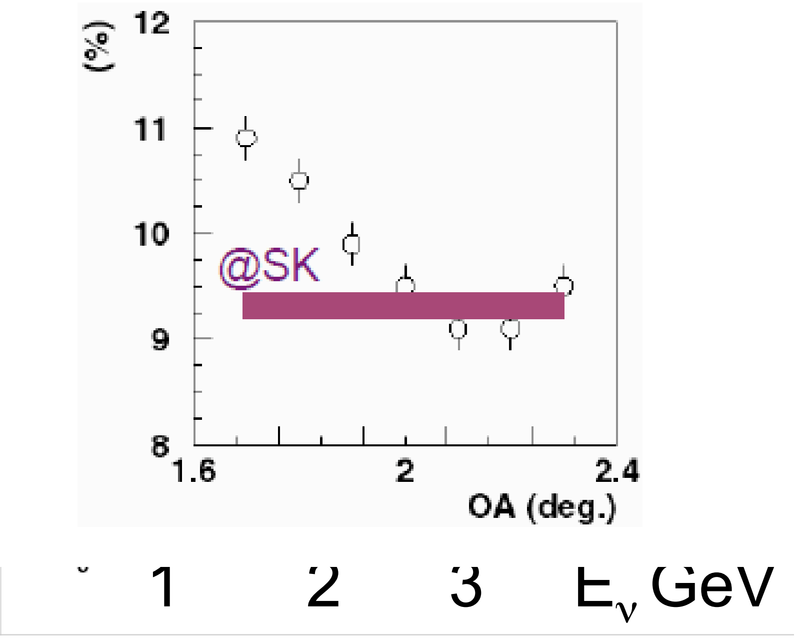
Experimental setup overview



- **Beam line**
- **Muon monitors @ ~140m**
  - Fast (spill-by-spill) monitoring of beam direction/intensity ($\pi \rightarrow \mu\ \nu$)
- **First near detector @280m**
  - Flux/spectrum/νe - off-axis
  - intensity/direction - on-axis
- **Far detector @ 295km**
  - Super-Kamiokande (50kt)

NC-π^0 / CC ratio

At 280m



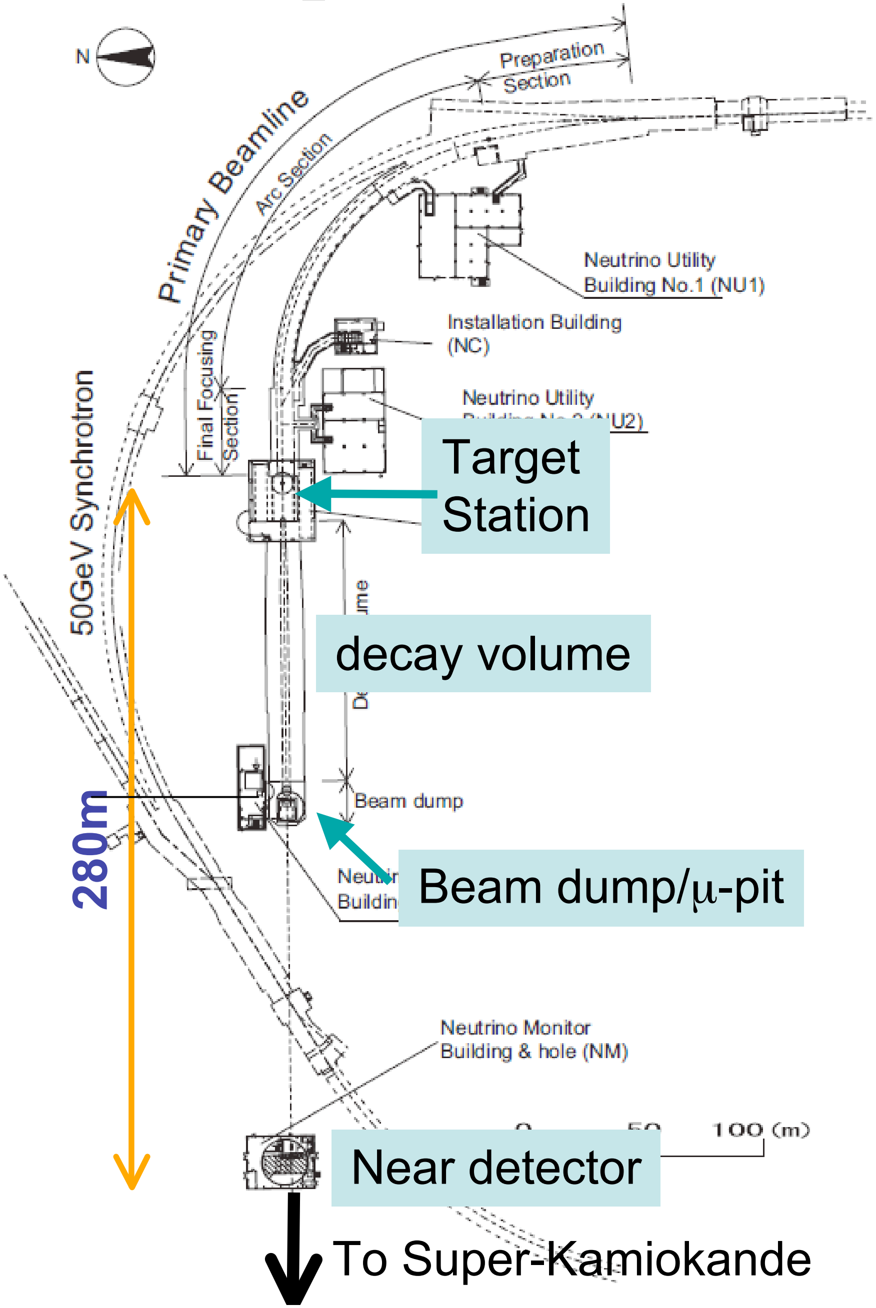
Components in T2K Experiment

Components

- Primary proton beam line
  - Normal conducting magnets
  - Superconducting arc
  - Proton beam monitors
- Target/Horn system
- Decay pipe
- Beam dump
- Muon monitors
- Near neutrino detector

Special Features

- **Superconducting combined function magnets**
- **Off-axis beam**



External reviews on T2K

- International Advisory Committee has been endorsing the highest priority for T2K (2002, 03, 04, 05, 06)
- Neutrino Technical Advisory Committee (Reviewers from FNAL, TRIUMF, CERN and KEK) has reviewed technical aspects of beam line (Nov. 12,13, 2003, Apr. 26~28, 2005)
- Radiation Safety Review Committee has been formed and will conclude within this fiscal year

Beam line status (examples)

- Super-Conducting magnet has been fully tested at I=7700A (eq. 50 GeV) without quench
  - mass production started
- Vacuum window design and prototyping at RAL
  - To be fixed in a month
- Horn magnet long term test has been started
  - Started the test at 320kA (full current) yesterday!
- Target
  - Thermal shock wave analysis, CFD analysis, erosion, oxidization
  - Manufacturing methods established (graphite rod, Ti tubing)
  - 1/20 scale cooling test done
  - Helium circulation system purchased

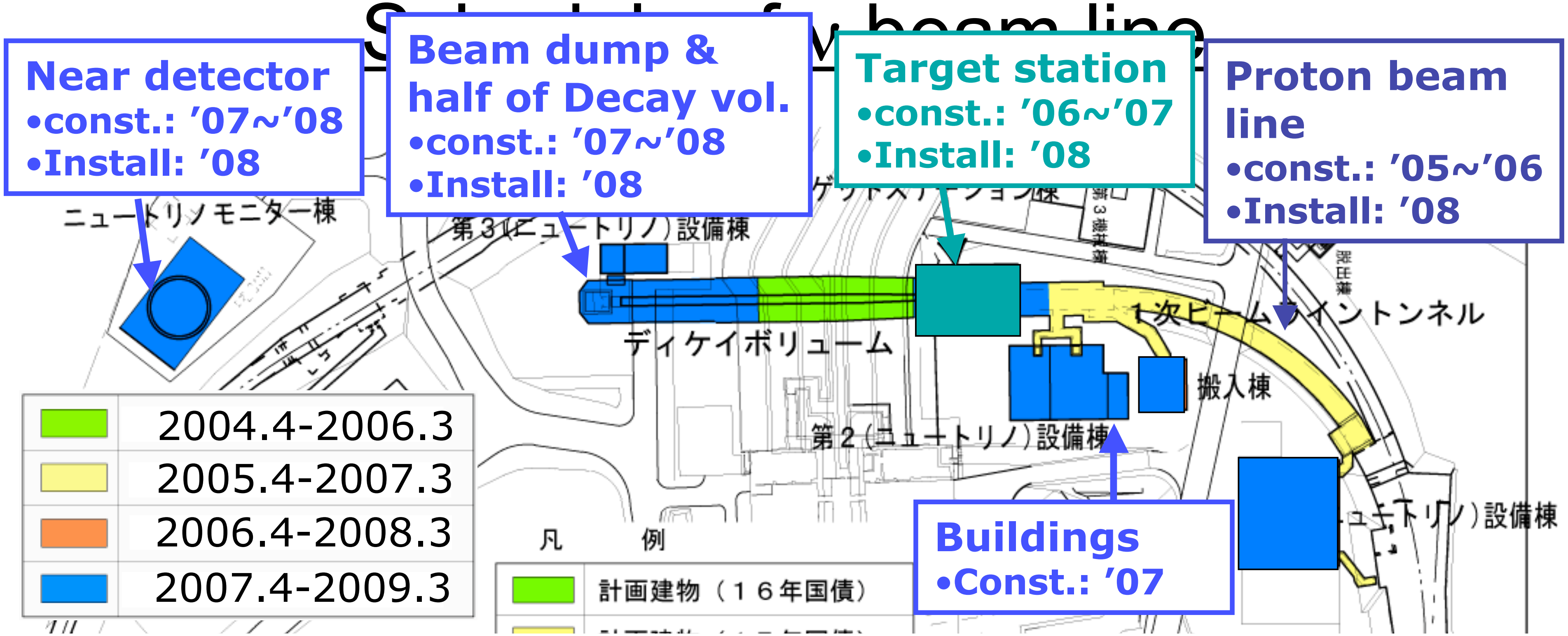
- Beam line construction detailed design completed

Summary of Status

	Conceptual Design	Engineering Design	Real Production	Installation	Operation test
Proton Beam monitor	Partially	Starting	2006~	2007~	2008
Superconducting magnets	Done	Done	~10%	2008	2008
Cryogenics	🟦	🟦	2006~	2008	2008
Normal Conducting magnets	🟦	🟦	~25%	2007~	2008
Vacuum system	🟦	🟨	2006~	2007~	2008
Target	🟦	🟨		2008	2008
Horn	🟦	🟨		2008	2008
Target Station	🟦	🟦	2006~	2007~	2008
Beam Window	Starting			2008	2008
Decay Volume	🟦	🟦	🟦	~60%	2008
Beam Dump	🟦	🟨	2006~	2008	2008
Muon monitor	🟦			2008	2008

- Working design in hand for most of the components
- Shifting to prototyping, final engineering design, production

beam line



Near detector
- const.: ’07~’08
- Install: ’08

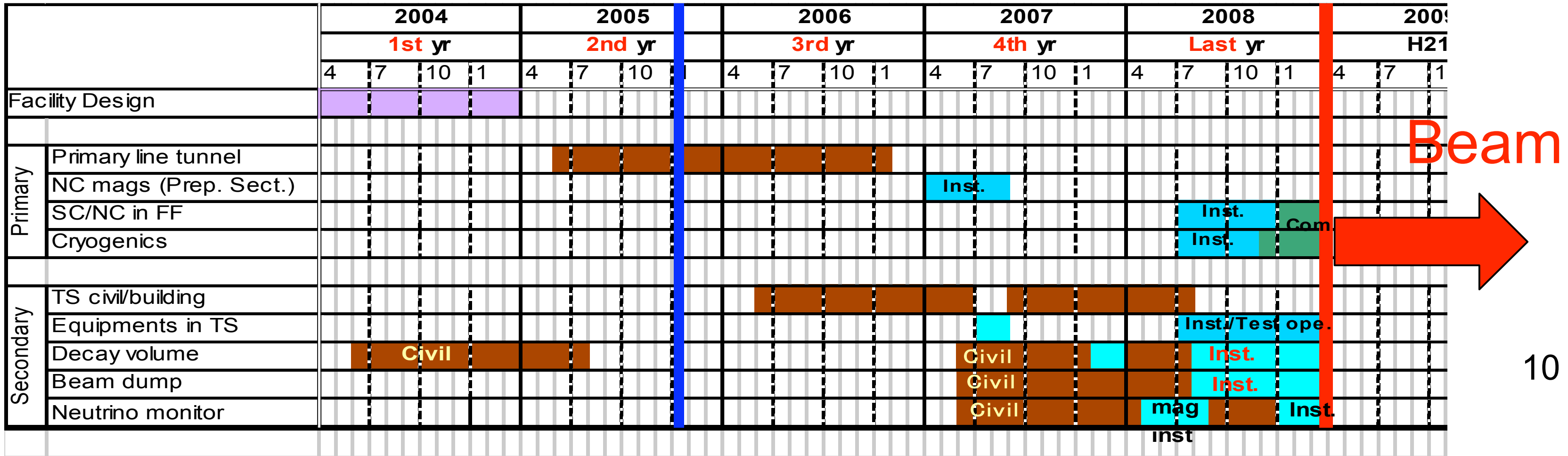
Beam dump & half of Decay vol.
- const.: ’07~’08
- Install: ’08

Target station
- const.: ’06~’07
- Install: ’08

Proton beam line
- const.: ’05~’06
- Install: ’08

Buildings
- Const.: ’07

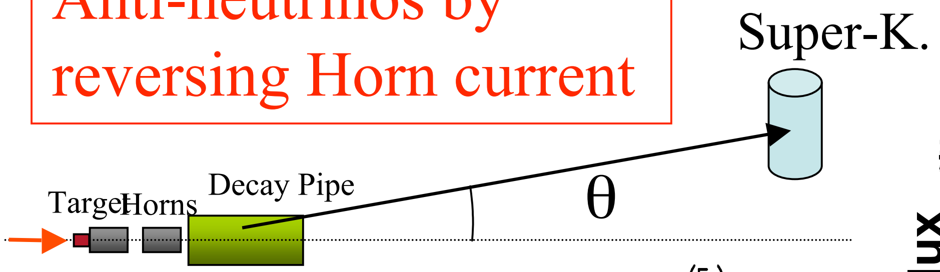
🟩	2004.4-2006.3
🟨	2005.4-2007.3
🟧	2006.4-2008.3
🟦	2007.4-2009.3



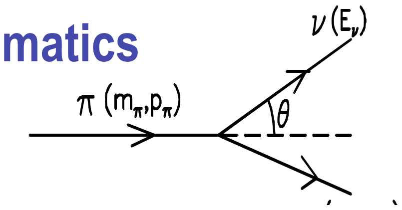
Main features of T2K

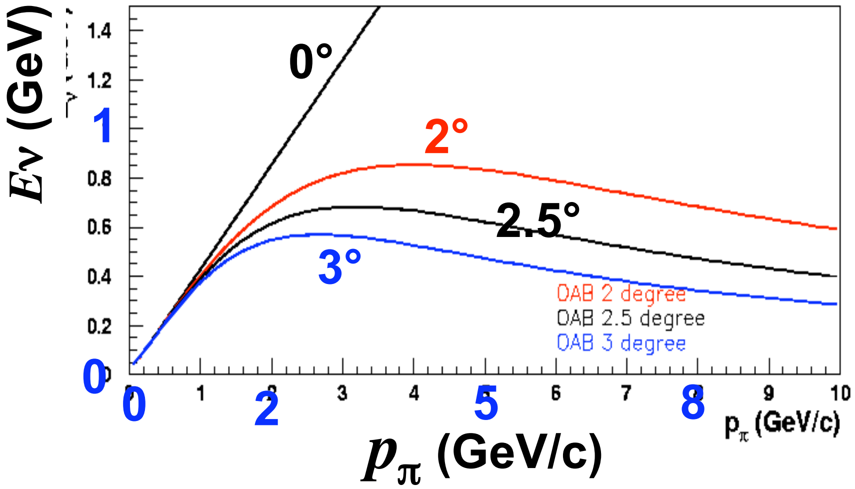
Narrow intense beam: Off-axis beam

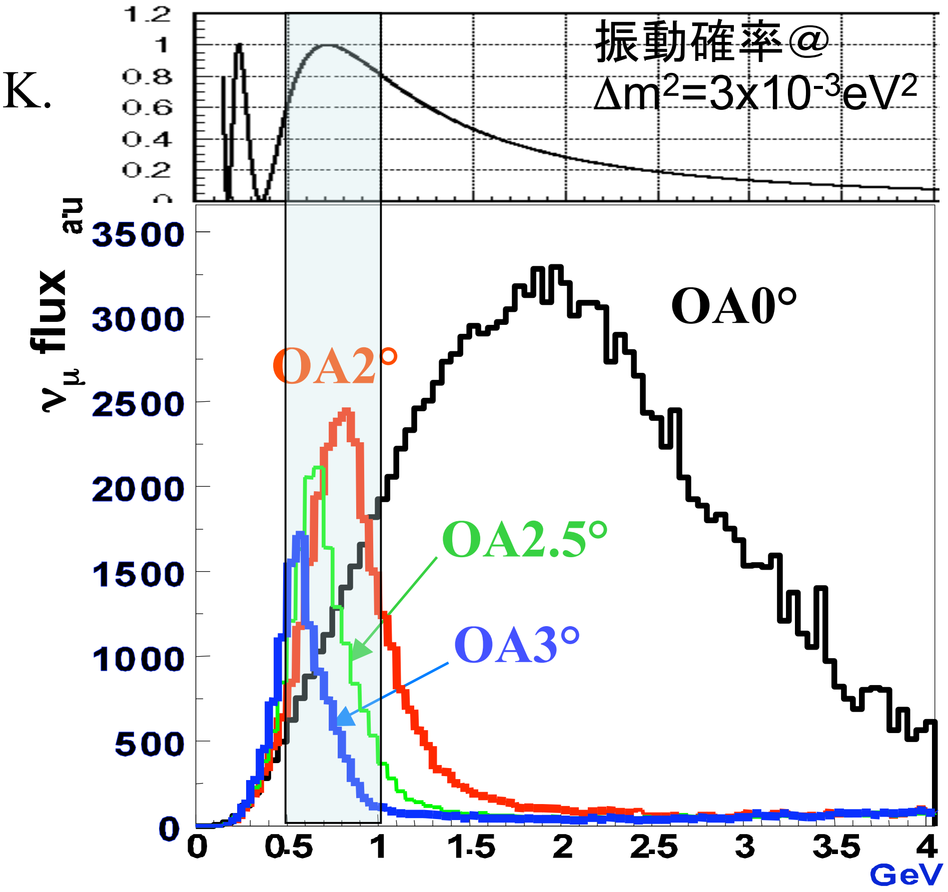
Anti-neutrinos by reversing Horn current



π decay Kinematics







- **Quasi Monochromatic Beam**
- **x 2~3 intense than NBB**
- **Tuned at oscillation maximum**

Statistics at SK

(OAB 2.5 deg, 1 yr, 22.5 kt)

~ 2200 ν_μ tot

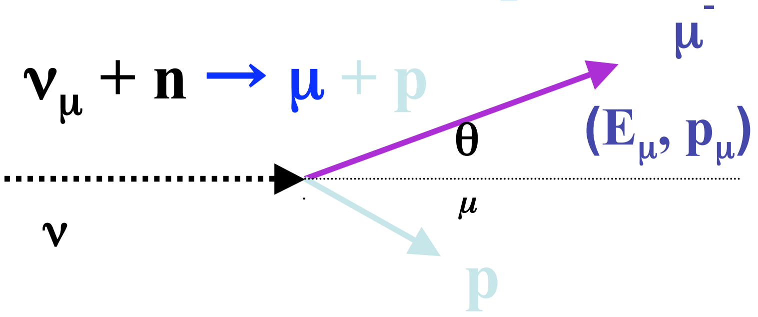
~ 1600 ν_μ CC

ν_e ~0.4% at ν_μ peak

Eν reconstruction at low energy

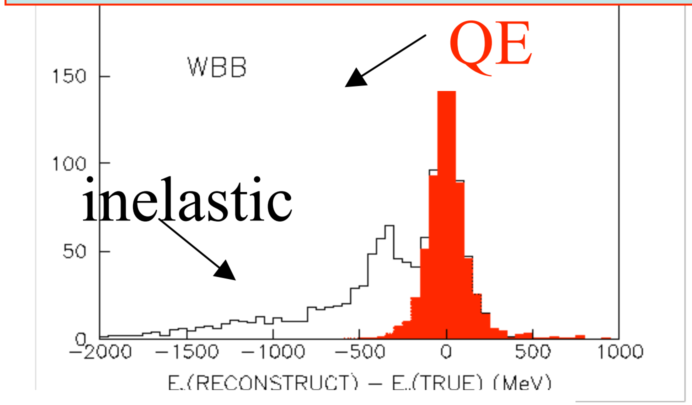
Quasi-Elastic process

$\nu_\mu + n \rightarrow \mu + p$



$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

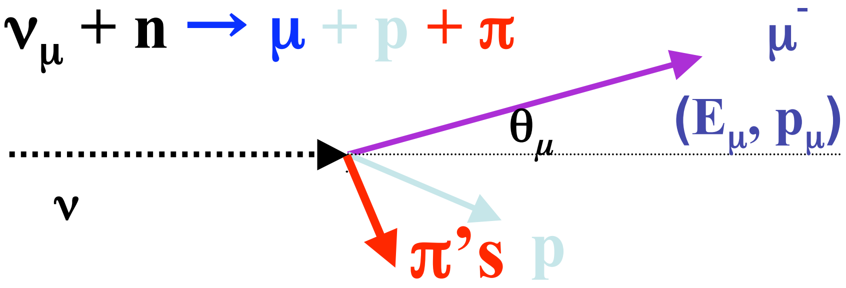
δE ~ 60 MeV δE/E ~ 10%



E_ν (reconstructed) – E_ν (true)

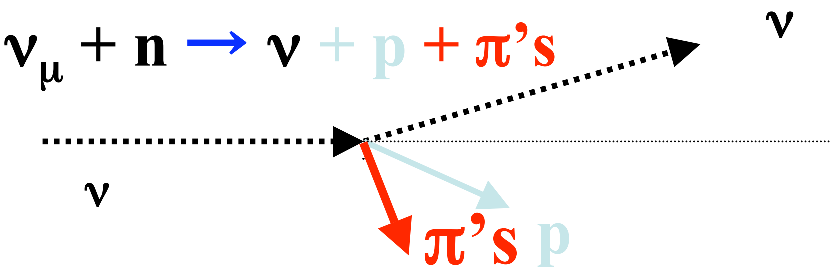
CC 1π

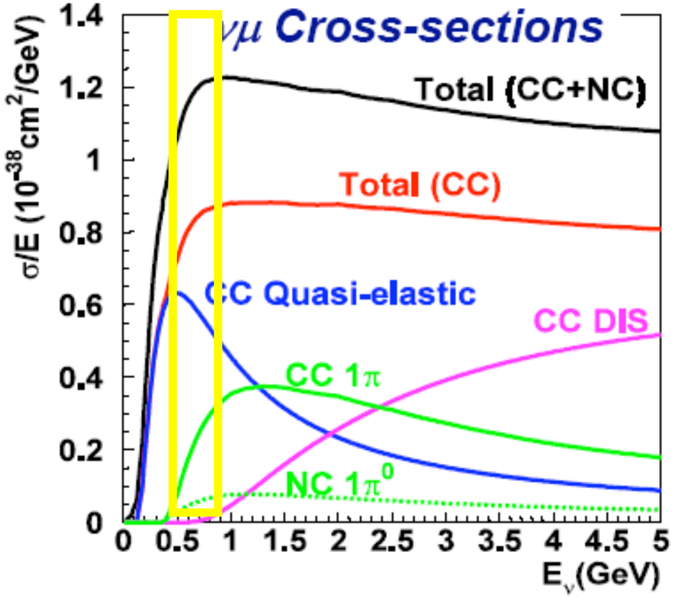
$\nu_\mu + n \rightarrow \mu + p + \pi$



NC 1π

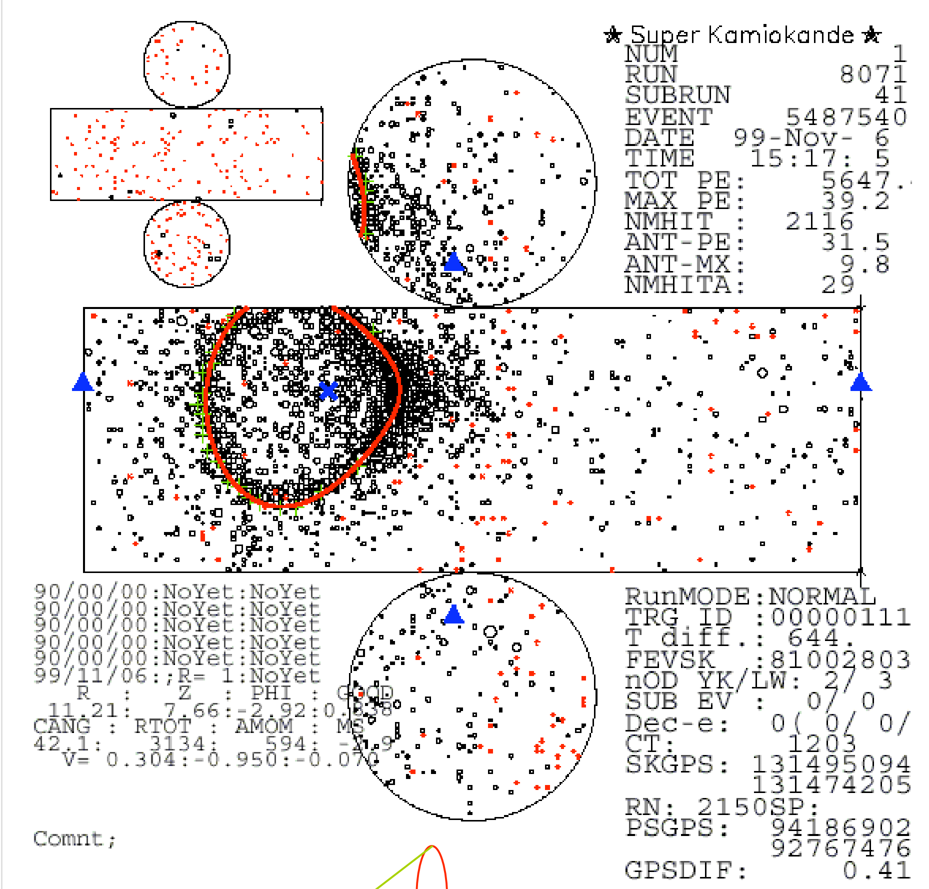
$\nu_\mu + n \rightarrow \nu + p + \pi$'s





PID in SK

e-like

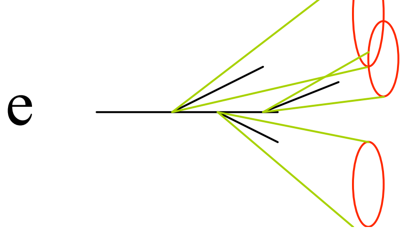


```
★ Super Kamiokande ★
NUM                1
RUN             8071
SUBRUN            41
EVENT        5487540
DATE      99-Nov- 6
TIME       15:17: 5
TOT PE:       5647.
MAX PE:        39.2
NMHIT  :    2116
ANT-PE:        31.5
ANT-MX:         9.8
NMHITA:       29
```

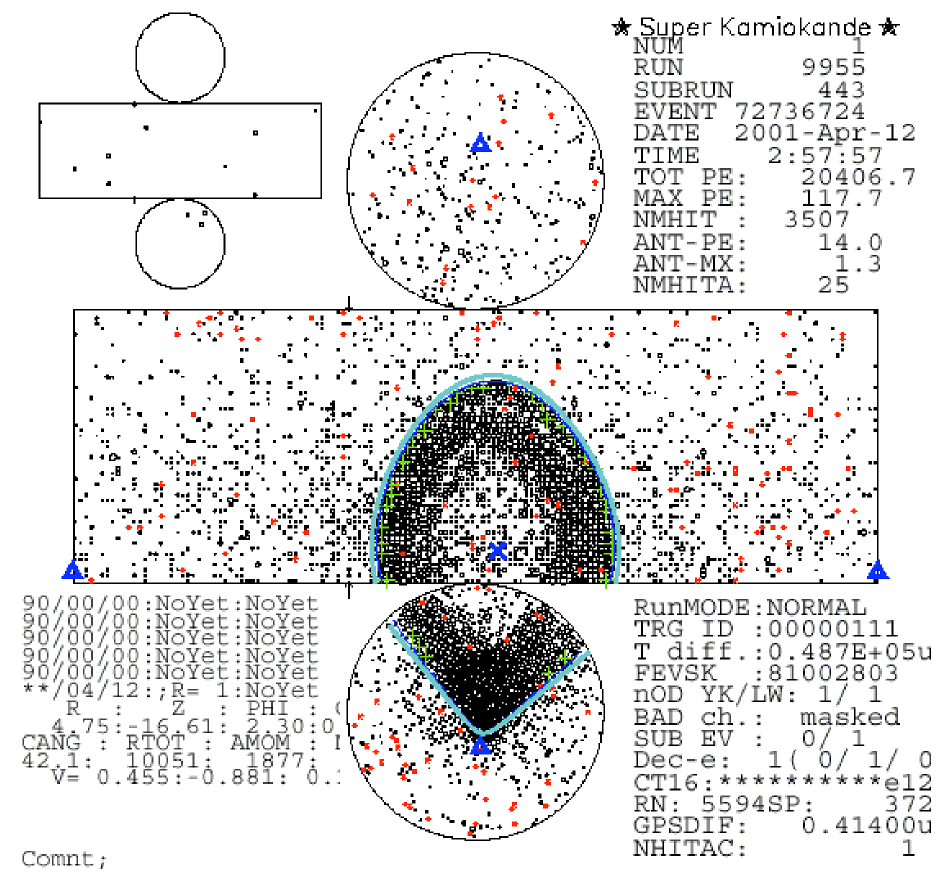
```
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
99/11/06:;R= 1:NoYet
  R  :   Z  : PHI : GOOD
 11.21:  7.66:-2.92:0.838
CANG : RTOT : AMOM : MS
42.1:   3134:   594: -21.9
  V= 0.304:-0.950:-0.070

Comnt;
```

```
RunMODE:NORMAL
TRG ID :00000111
T diff.: 644.
FEVSK  :81002803
nOD YK/LW: 2/ 3
SUB EV  :  0/ 0
Dec-e:  0( 0/ 0/
CT:         1203
SKGPS: 131495094
       131474205
RN: 2150SP:
PSGPS:  94186902
        92767476
GPSDIF:     0.41
```



μ-like

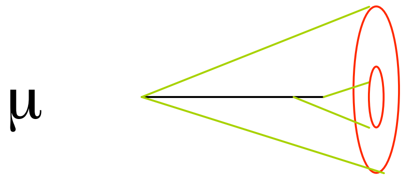


```
★ Super Kamiokande ★
NUM             1
RUN          9955
SUBRUN        443
EVENT    72736724
DATE   2001-Apr-12
TIME      2:57:57
TOT PE:   20406.7
MAX PE:     117.7
NMHIT  :  3507
ANT-PE:      14.0
ANT-MX:       1.3
NMHITA:     25
```

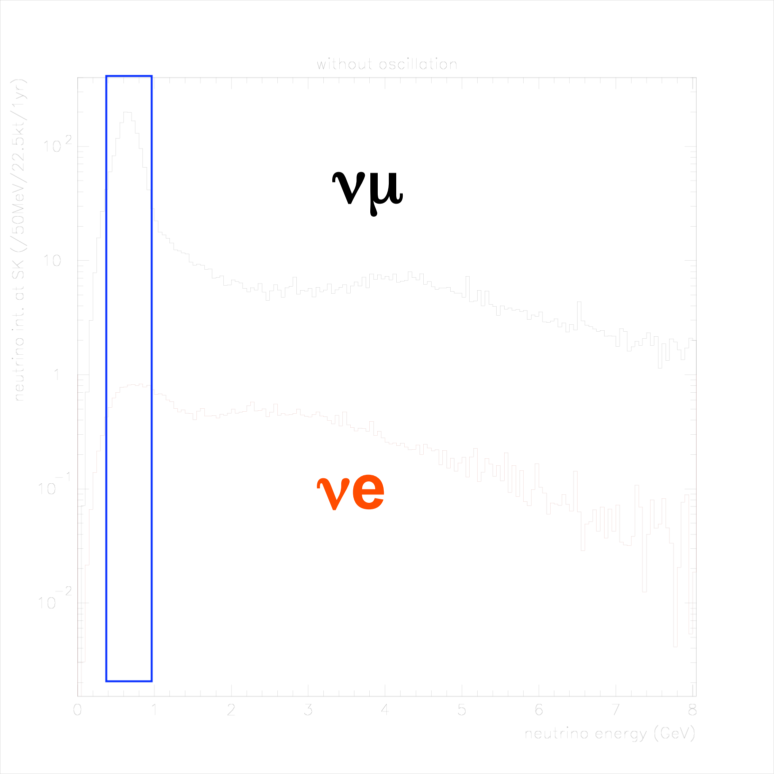
```
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
**/04/12:;R= 1:NoYet
  R  :   Z  : PHI : (
 4.75:-16.61: 2.30:0
CANG : RTOT : AMOM : I
42.1:  10051:  1877:
  V= 0.455:-0.881: 0.

Comnt;
```

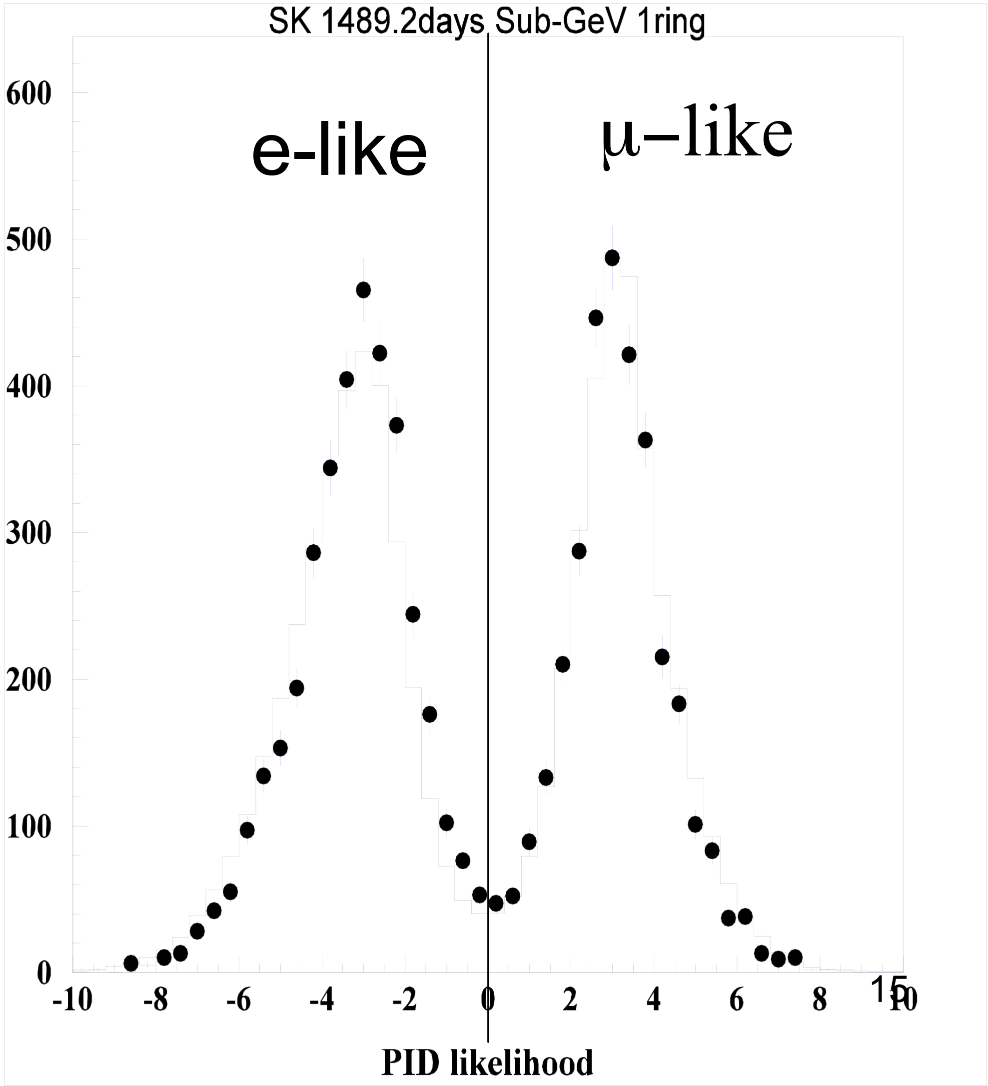
```
RunMODE:NORMAL
TRG ID :00000111
T diff.:0.487E+05u
FEVSK  :81002803
nOD YK/LW: 1/ 1
BAD ch.:  masked
SUB EV  :  0/ 1
Dec-e:  1( 0/ 1/ 0
CT16:**********e12
RN: 5594SP:    372
GPSDIF:  0.41400u
NHITAC:          1
```



Particle ID (e & μ) (in single ring events)



Super-Kamiokande
Atmospheric data



10% measurement on NCπ^0 in 280m near detector

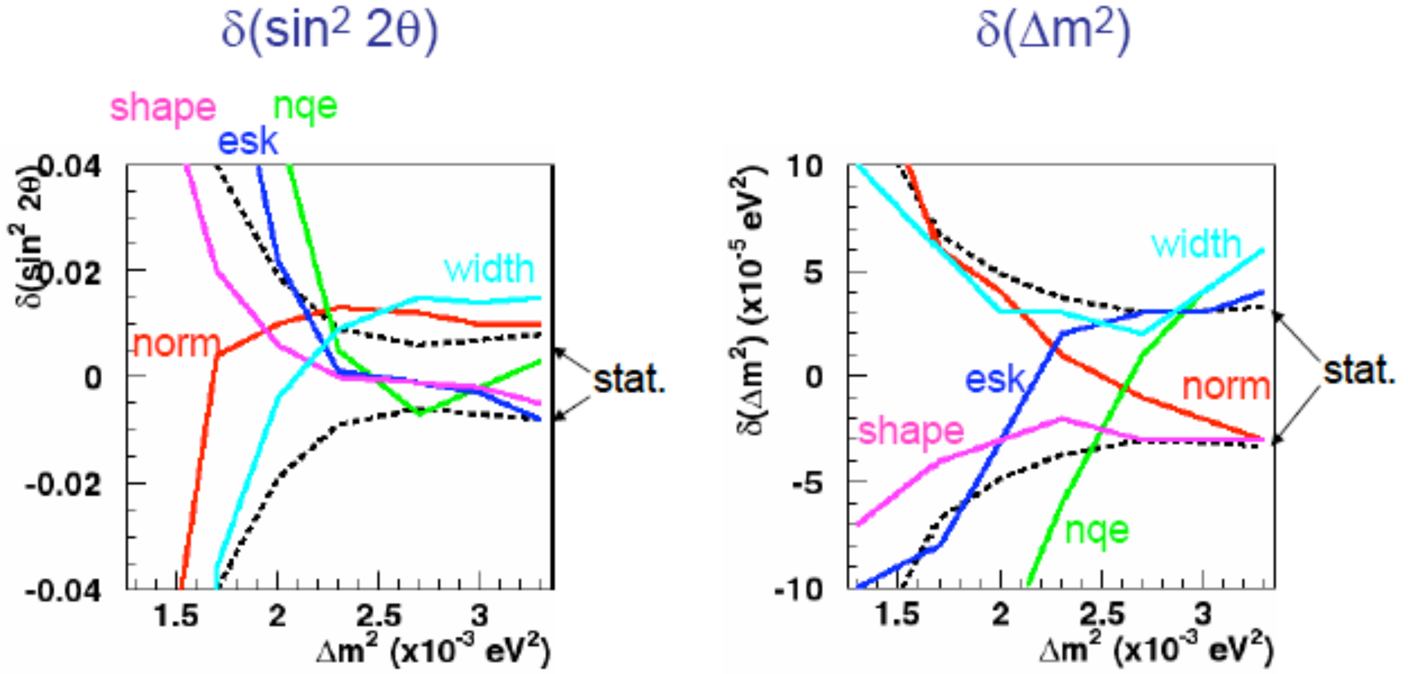
BKGs become to 1/3 by E_{rec} requirement

Precision measurement of θ_{23} , Δm^2_{23} possible systematic errors sources

- Systematic errors and assumed knowledge
  - **normalization (10% （5%(K2K))**
  - **non-QE/QE ratio (20% (to be measured))**
  - **E scale (4% (2%@K2K))**
  - **Spectrum shape (Fluka/MARS →(Near D.))**
  - **Spectrum width (10%)**

Set at OA 2.5^o

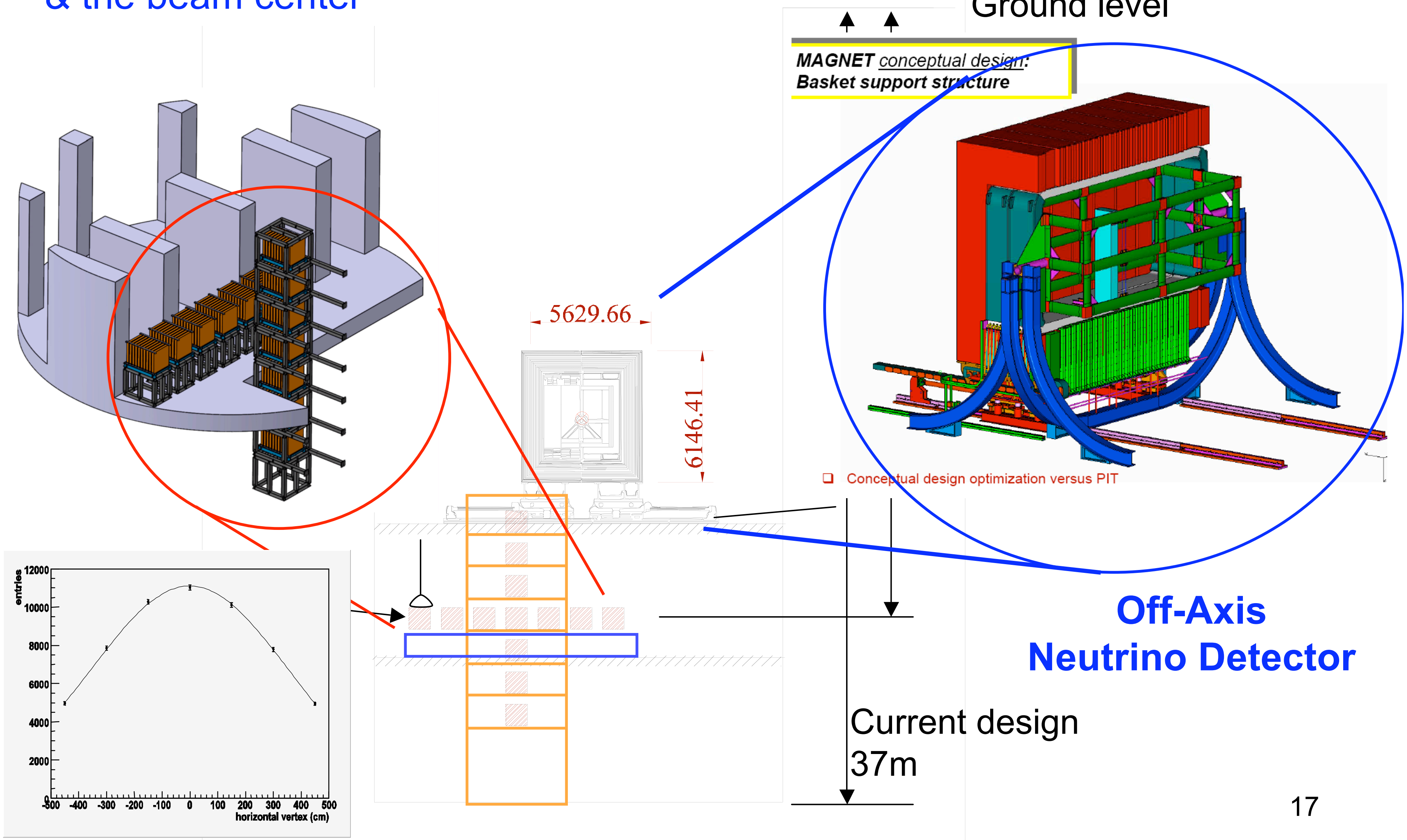
$\delta(\sin^2 2\theta_{23})$~0.01
$\delta(\Delta m^2_{23})$ <1×10^{-4} eV^2



ND280 Neutrino Detector
(Experimental Hall with 3 floors)

On-Axis ν monitor

Neutrino Profile
& the beam center



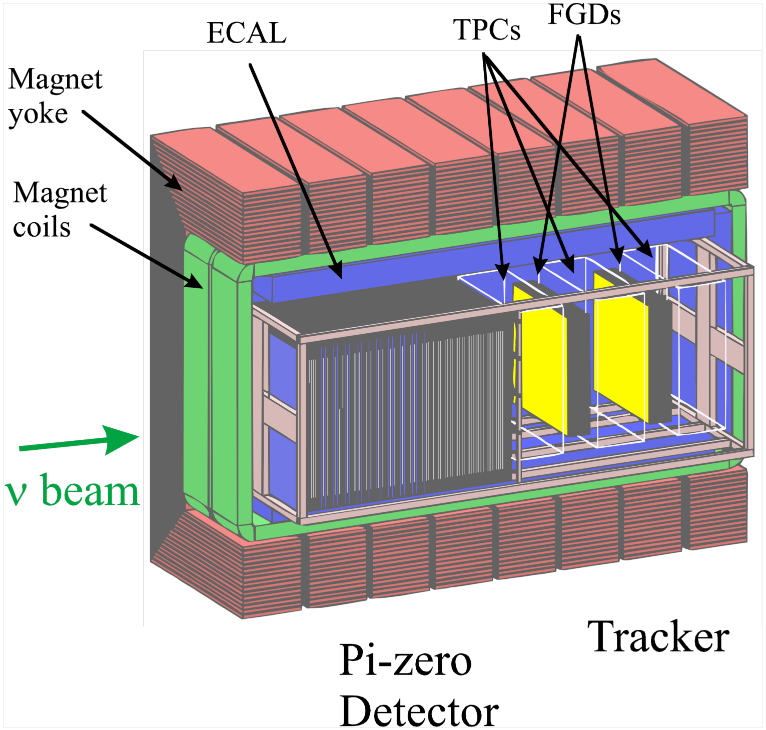
Ground level

Off-Axis
Neutrino Detector

Current design
37m

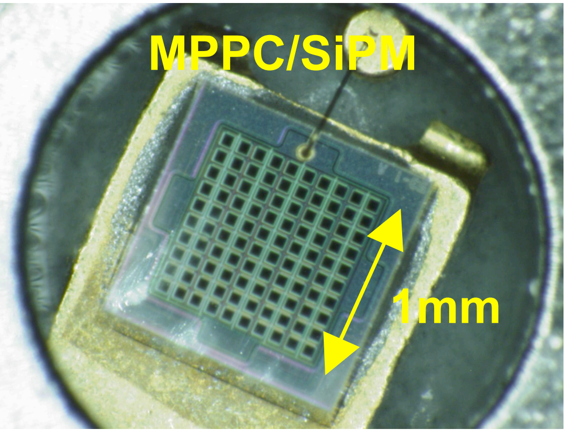
Off-Axis Neutrino Detector (by all countries)

- Measurement of ν flux and σ in the SK direction with magnet
  - ν_μ , ν_e and anti-ν_μ flux and the energy spectrum.
  - Quasi-Elastic (Signal for E_ν reconstruction)
  - Inelastic $\pi^{\pm,0}$ production (background for beam understanding)
- Detector components.
  - TPC
  - Fine-Grained Scintillator detector (FGD) for CC interaction.
  - Lead/Scintillator tracking detector for π^0
  - Electron Calorimeter
  - Muon Range Detector

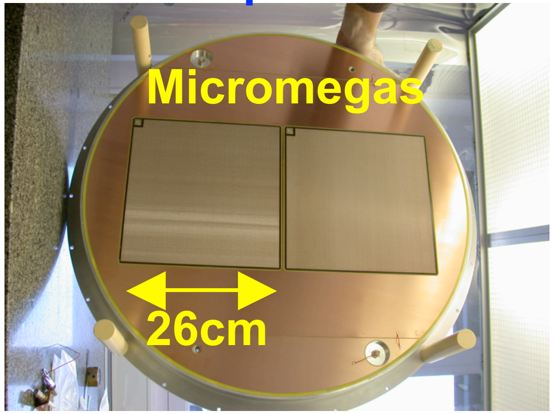


New Technology

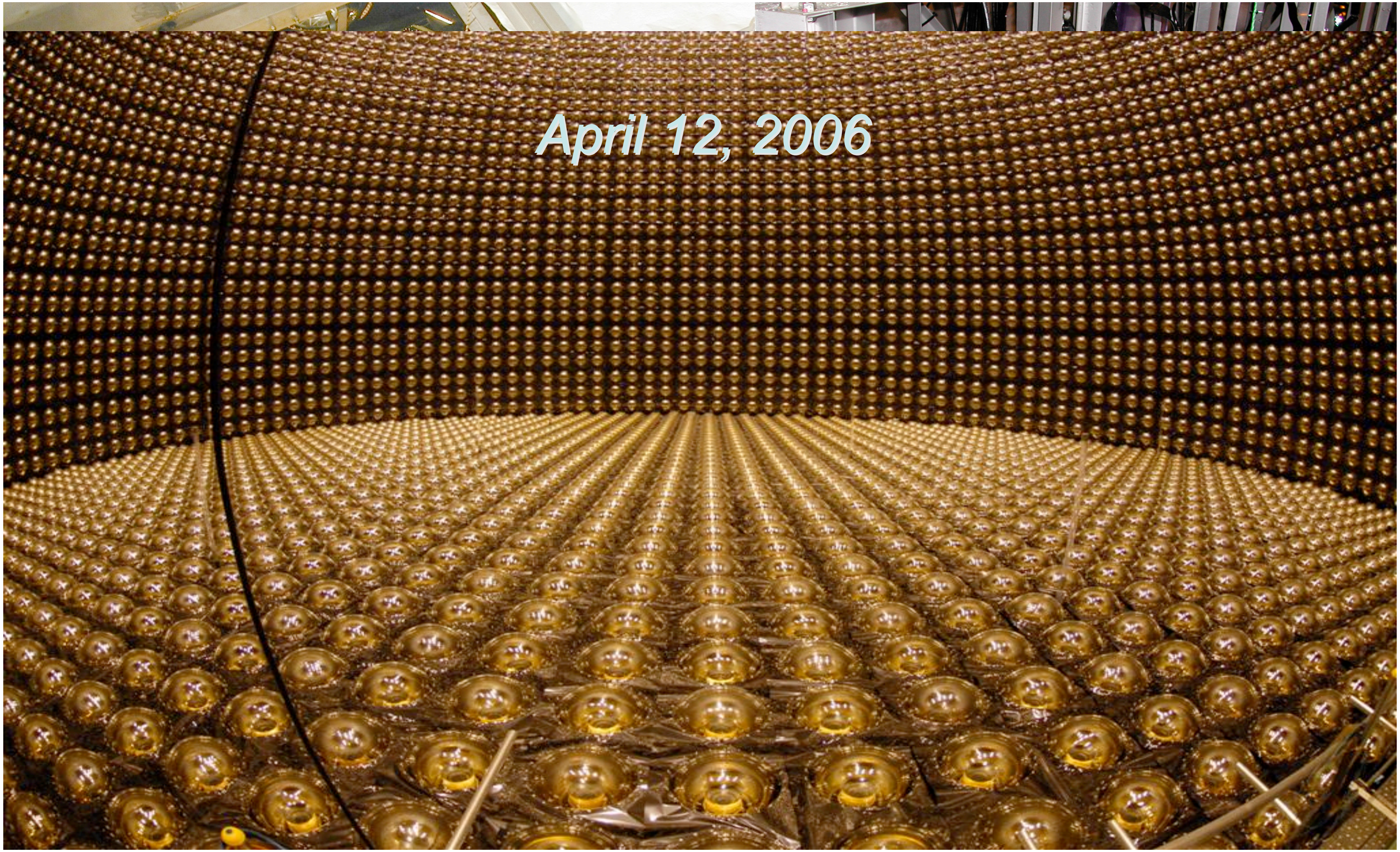
Photo-Sensor



Gas-amplification



◄ Complete R&D
→ mass production



April 12, 2006

Super Kamiokande has been fully rebuild

Physics sensitivities

Three contributions in ν_e appearance

$$P(\nu_\mu \to \nu_e) = 4C_{13}^{\ 2}\underline{S_{13}^{\ 2}}S_{23}^{\ 2}\sin^2\Phi_{31}$$

θ_{13}

$$+8C_{13}^{\ 2}S_{12}\underline{S_{13}}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\underline{\sin\Phi_{21}}$$

CP conserving

$$-8C_{13}^{\ 2}C_{12}C_{23}S_{12}\underline{S_{13}}S_{23}\underline{\sin\delta}\sin\Phi_{32}\sin\Phi_{31}\underline{\sin\Phi_{21}}$$

$\cancel{\text{CP}}$

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

solar ν

$$-8C_{13}^{\ 2}\underline{S_{13}^{\ 2}}S_{23}^{\ 2}(1-2S_{13}^{\ 2})\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}$$

matter effect

mass hierarchy

$\Phi_{ij} = \Delta m_{ij}^2 L/4E$, $\boldsymbol{S_{ij}}$**=sin**$\boldsymbol{\theta_{ij}}$, $\boldsymbol{C_{ij}}$**=cos**$\boldsymbol{\theta_{ij}}$

L : flight length, E : neutrino energy,

$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$, m_i : mass eigenvalues

$\delta \to -\delta$, $a \to -a$ for $\bar{\nu}_\mu \to \bar{\nu}_e$

Small numbers
- S_{31}
- $\sin\Phi_{21} \sim 0.03$

$$\frac{aL}{4E} = 7.6\times\left(\frac{\rho}{[g/cm^3]}\right)\left(\frac{E}{[GeV]}\right)\left[\frac{L}{4E}\right] \sim 2\rho L$$

- $L/E \sim 3 \times 10^2$ (km/GeV),
  Φ_{32} $(=(m_3^2 - m_2^2)L/4E) \sim \Phi_{31} \sim \pi/2$, $\Phi_{12} \sim 0.03$

- $\nu_\mu \rightarrow \nu_e$ three contributions

1 Term which is same for neutrinos and anti-neutrinos
2 CP violating term
3 Matter effect (proportional to L or E at constant L/E)

- It is almost impossible to change distance or neutrino energy

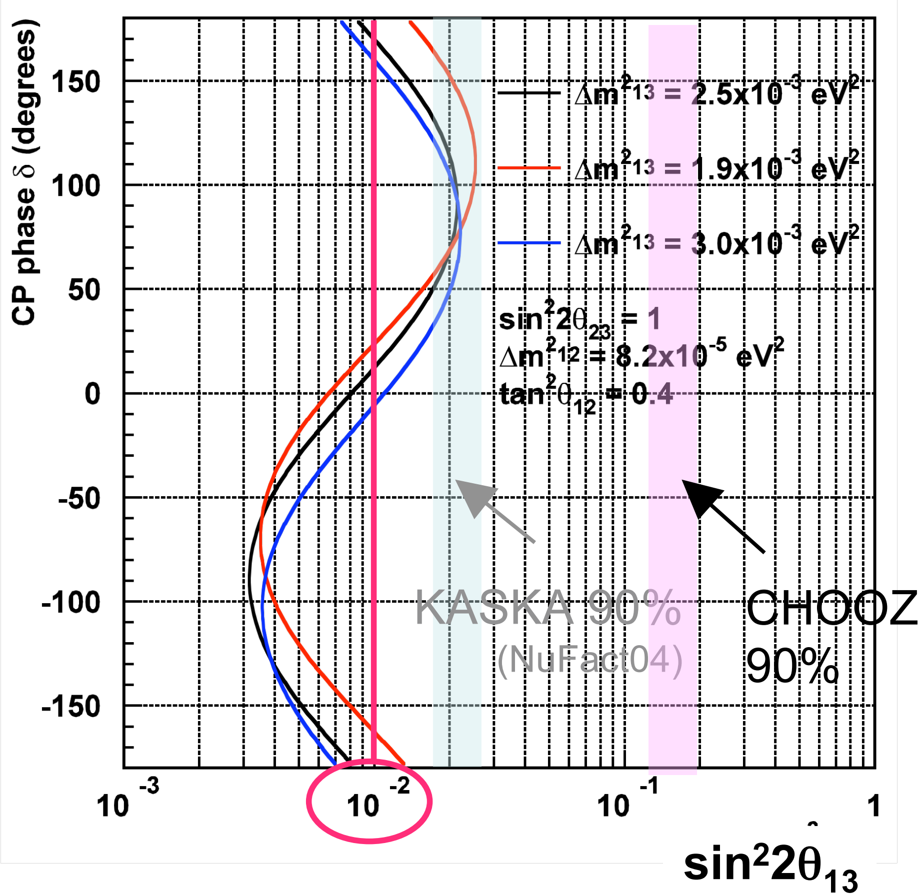
1. Compare Neutrinos and Anti-neutrinos
2. Compare with reactor data

- Make matter effect small by using low energy neutrinos !

T2K Physics Sensitivity

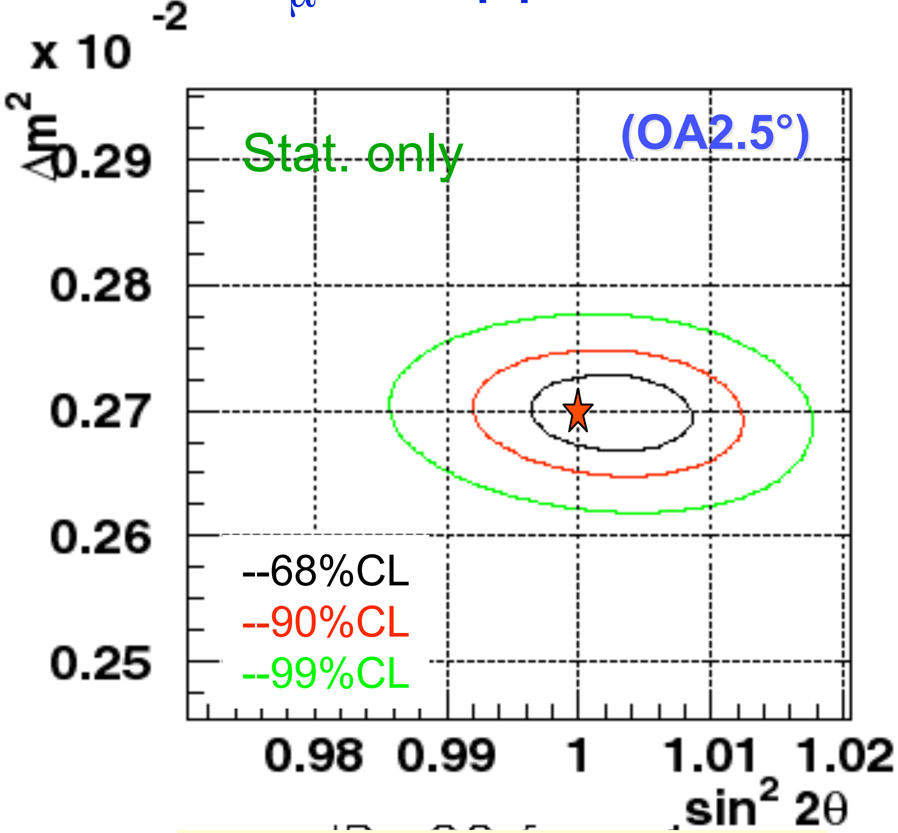
ν_e appearance

(Strong δ dependence)



>10 times improvement from CHOOZ

ν_μ disappearance



Goal

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

$\delta(\Delta m_{23}^2)\sim<1\times 10^{-4}$

Summary of main features of T2K

- 295 km baseline and Δm^2 (~$2.5\text{x}10^{-3}$ eV^2)
- Oscillation maximum occurs at sub-GeV neutrino energy
- Off-axis beam (low energy with small high energy tail)
  1. Two body reaction (ν n →μ p) dominates :Quasi elastic (QE)
     1. 1,2 prong events dominate → relatively easy PID
     2. Measurement of θ_μ, p_μ → E_ν can be calculated
     3. Small high energy tail → Small π^0 -BKG from in ν_e search
        → Small π^{+-}-BKG from Eν reconst.
  2. Negligible matter effect (to be sensitive to CP term (in the future))
- Super-Kamiokande as the far detector
  1. Analysis of water Cherenkov detector data has accumulated almost twenty years of experience
  2. K2K has demonstrated BG rejection in ν_e search
- Proper coverage of near detector(s)
  1. Cross section ambiguity (measurements at close distance)

- Accumulation of technologies on high power beam handling

Conclusion

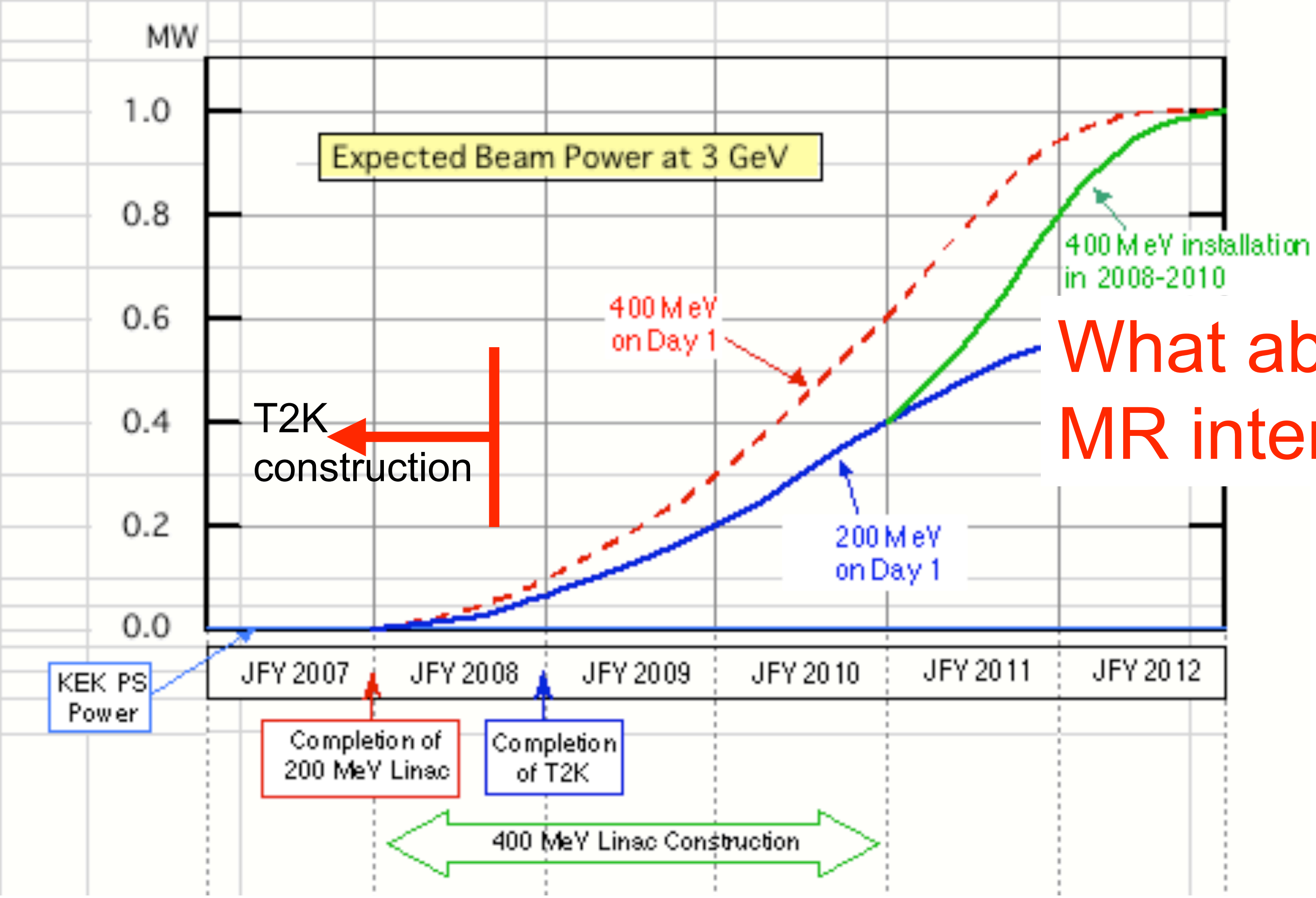
- Strong international team
- Discovery of finite neutrino mass is, so far the only one evidence beyond the 'Standard Model' and can be a window for unexpected and possibly ultra high energy physics
- Good beam energy-detector combination for high precision measurements

- Super-Kamiokande has been fully rebuild
- Intensive technical review have been done on beam line
  - Many difficulties have been overcome and the construction going well
- We can stay in budget for entire experiment
  - Inviting foreign contributions for improvements of the experiment
- Working hard to start experiment in Apr. 2009

Backup slides

MR intensity

3 GeV RCS commissioning plan



T2K construction

What about MR intensity?

Intensity of MR

- J-PARC start with 180 MeV LINAC

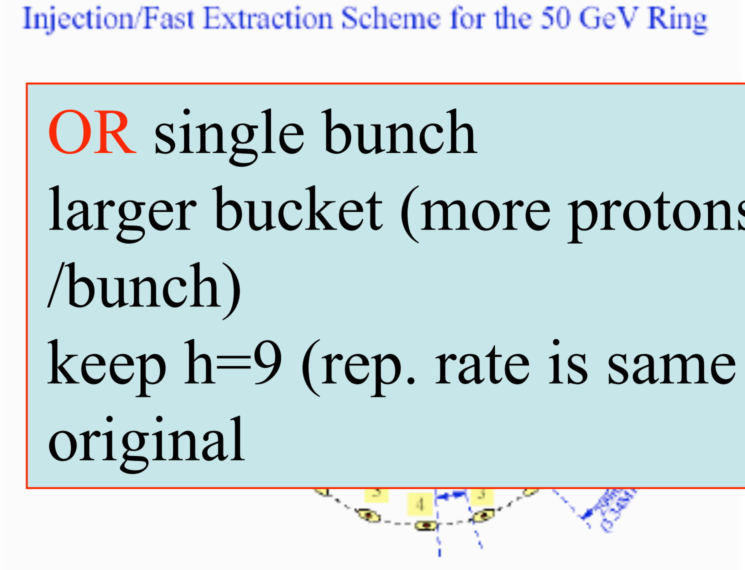
Currently, following realistic scenarios have been studied

- Intensity in 3 GeV Booster limited by space charge effect
  - increase number of bunches in MR by RF freq. increase in MR (injection time)
  - larger bucket in Booster to increase no. of protons/bunches
  - More RF power to increase rep. (with money)
- Every possible effort to increase MR intensity faster than 3GeV booster

- Badget request will be submitted to restore 400 MeV LINAC (2008,9,10 ?)
- Eventually more than MW beam

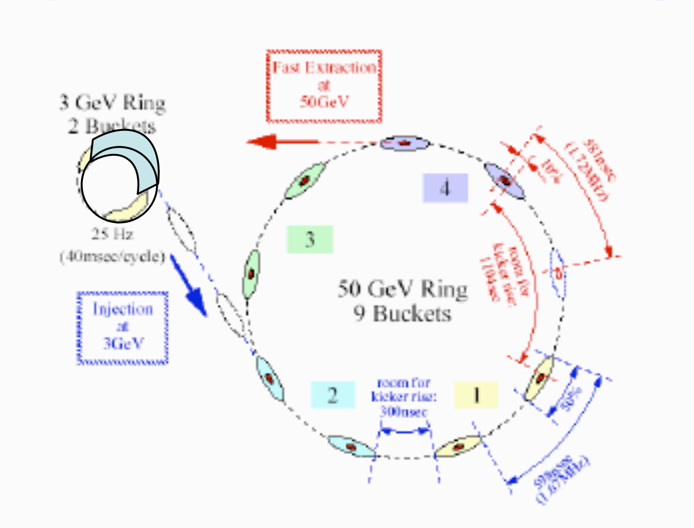
Injection Scheme to the 50 GeV MR

h = 18 (181-MeV injection)



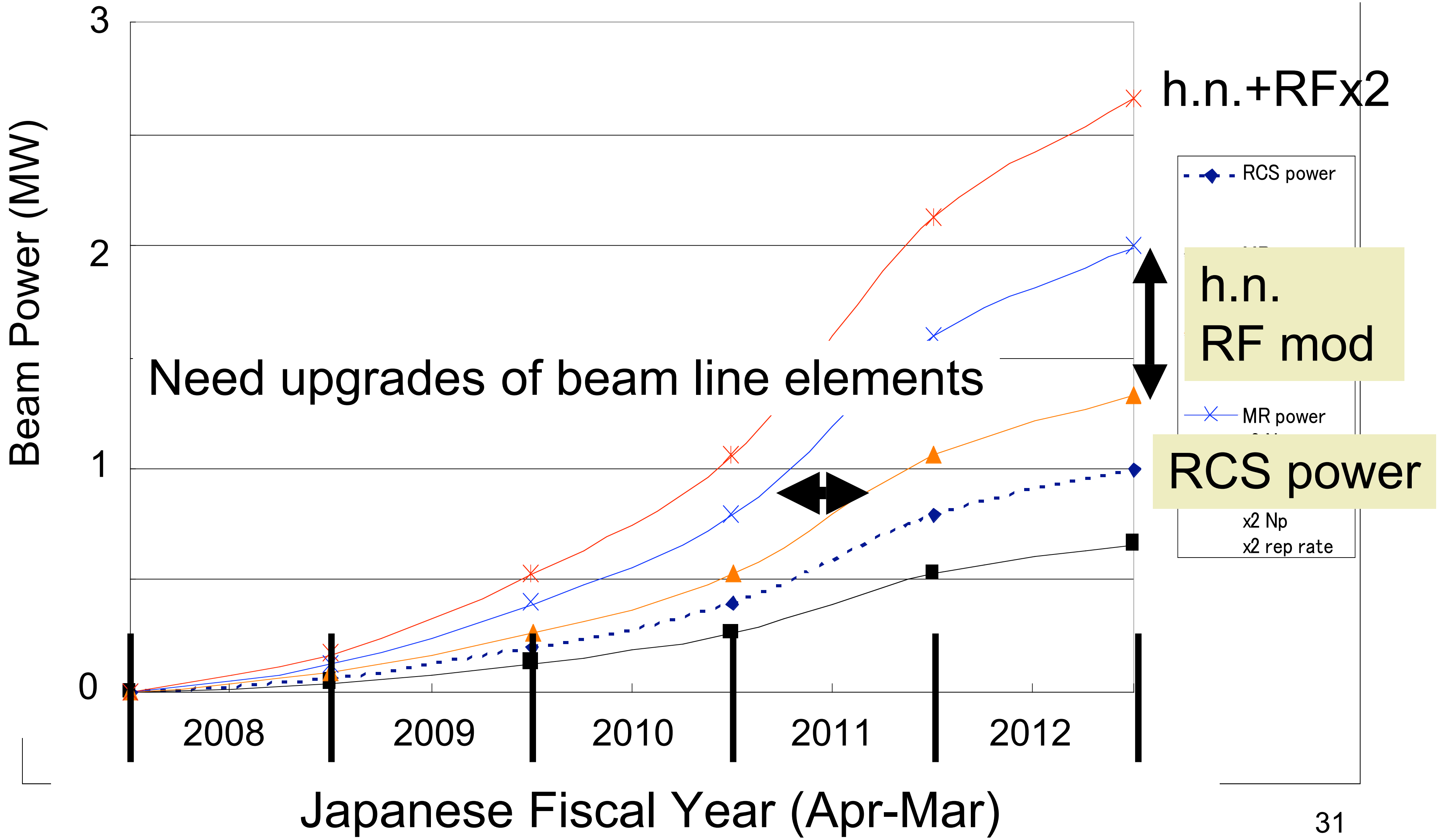
OR single bunch
larger bucket (more protons /bunch)
keep h=9 (rep. rate is same as original

h = 9 (400-MeV injection)



	h = 18	h = 9
Injection time	**560ms**	**120ms**
RF frequency	**3.34-3.44**	**1.67-1.72 MHz**
Injection kicker flat top	**130ns**	**900ns : PFN cable length**
Pulse bending magnet flat top	**600ms**	**120ms**
Injection kicker rise time	**170ns**	**300ns**

Accelerator commissioning plan



h.n.+RFx2

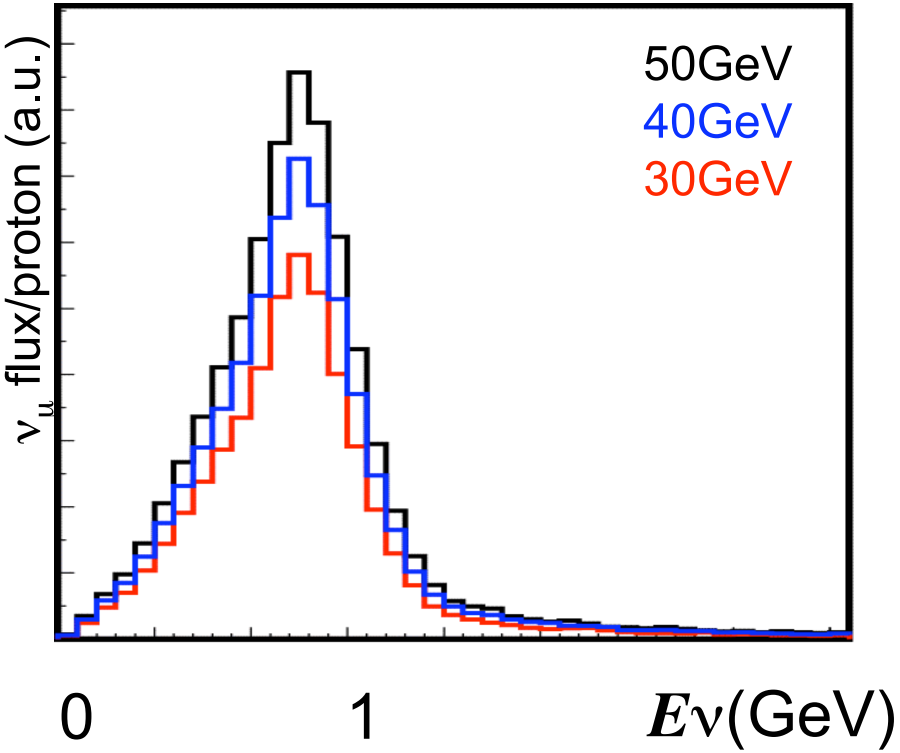
h.n.
RF mod

Need upgrades of beam line elements

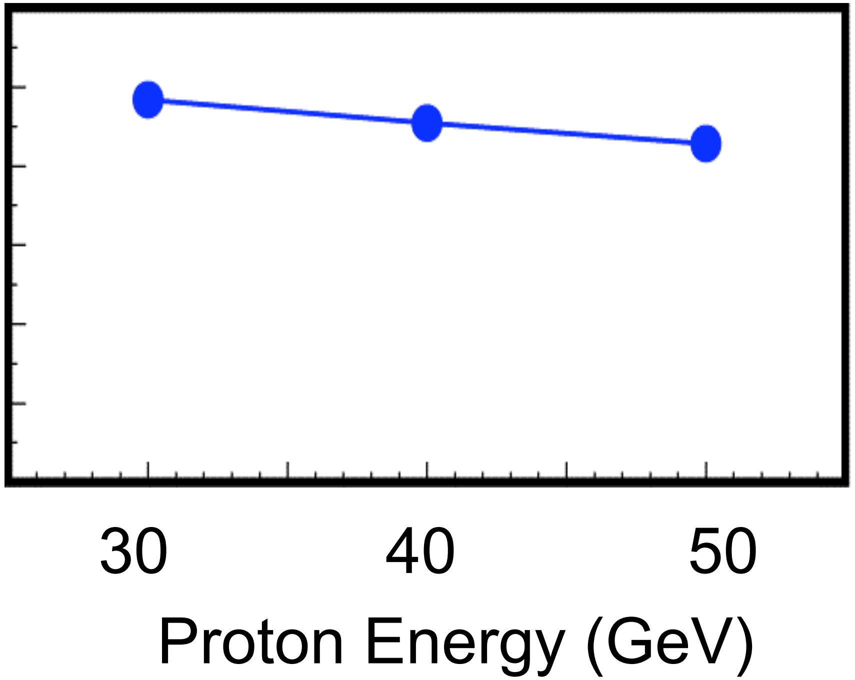
RCS power

Requirement on Proton Energy

Neutrino Flux $\propto$ ~ Proton beam power ($\boldsymbol{E}_{\mathbf{p}}$ x $\boldsymbol{N}$)



Peak Neutrino Flux
normalized by Beam power



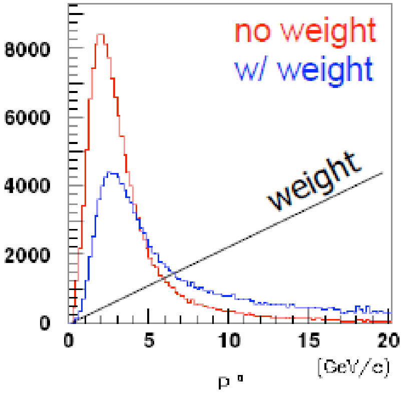
$\sin^2 2\theta_{13}$ 3σ—Discovery limit

	2009	10	11	12	14	15
MINOS OPERA	0.11	0.09	0.08	0.075	0.06	
D.Chooz	0.09 (0.21)	0.05 (0.18)	0.05 (0.18)			
T2K	0.75MW within 2010	0.5MW	0.05 0.08	0.03	0.02	0.018

(Nova) 0.05
Daya Bay ??? ← 0.015 →?????

Assumptions

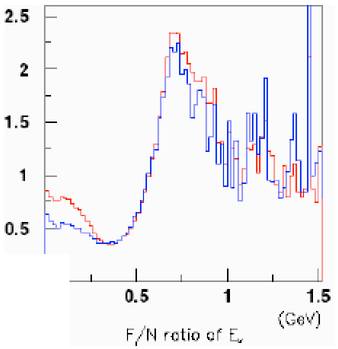
MINOS : $2\text{x}10^{20}$ POT/year CNGS too small detectors
Double Chooz : 2008 new near detector assumed
Nova : if funding start in 2007.10
Present limit (Chooz) $\sin^2 2\theta_{13} < 0.14$ @90%CL



Shift to high systematically

The change
- Peak momentum ~ +30%
- Average momentum ~ +160%

Change of Far/Near ratio



Far/Near ratio also hardly changed!

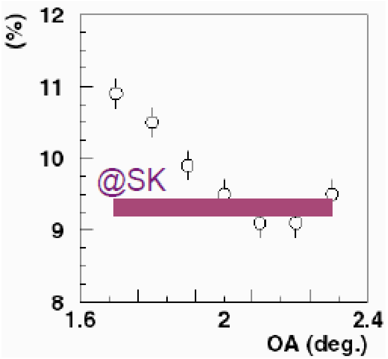
The difference is less than 5% at 0.3GeV<Eν<0.8GeV

Fraction of interaction mode

	CC		NC	
	QE	other	1π^0	other
SK	37.4%	34.2%	4.9%	23.5%
Off-axis	38.2%	33.0%	4.4%	24.4%
On-axis	19.2%	54.5%	5.3%	21.0%

At SK and ND off-axis position, 1/3 of all interactions is CCQE.

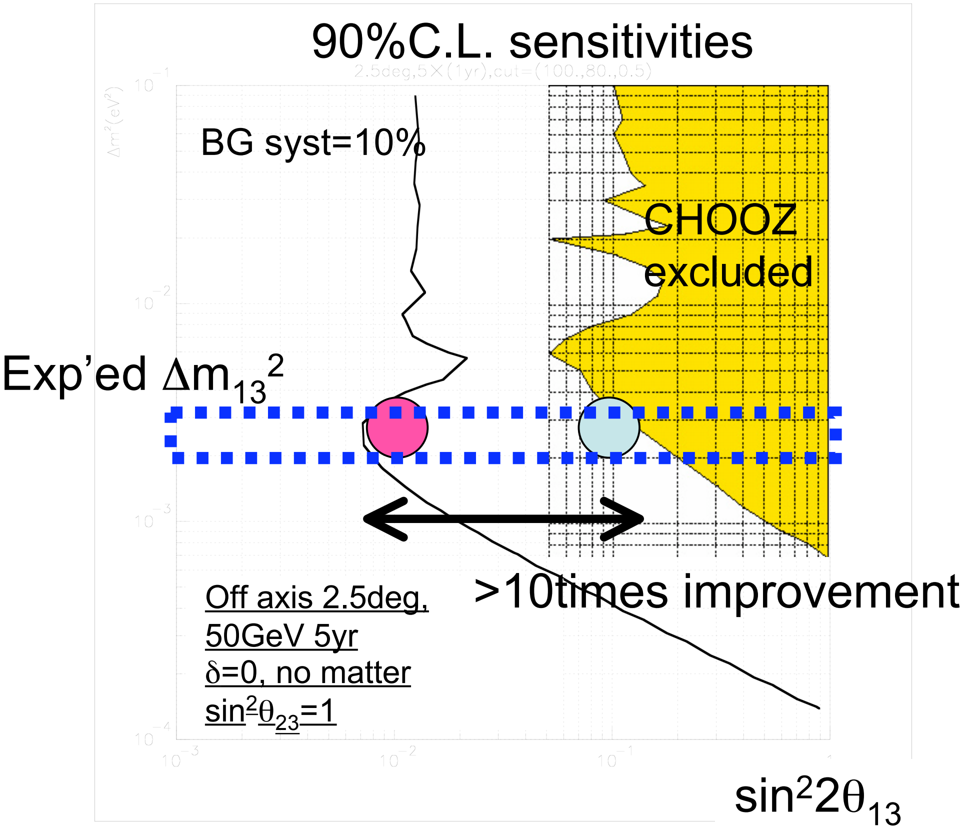
NC-π^0 / CC ratio

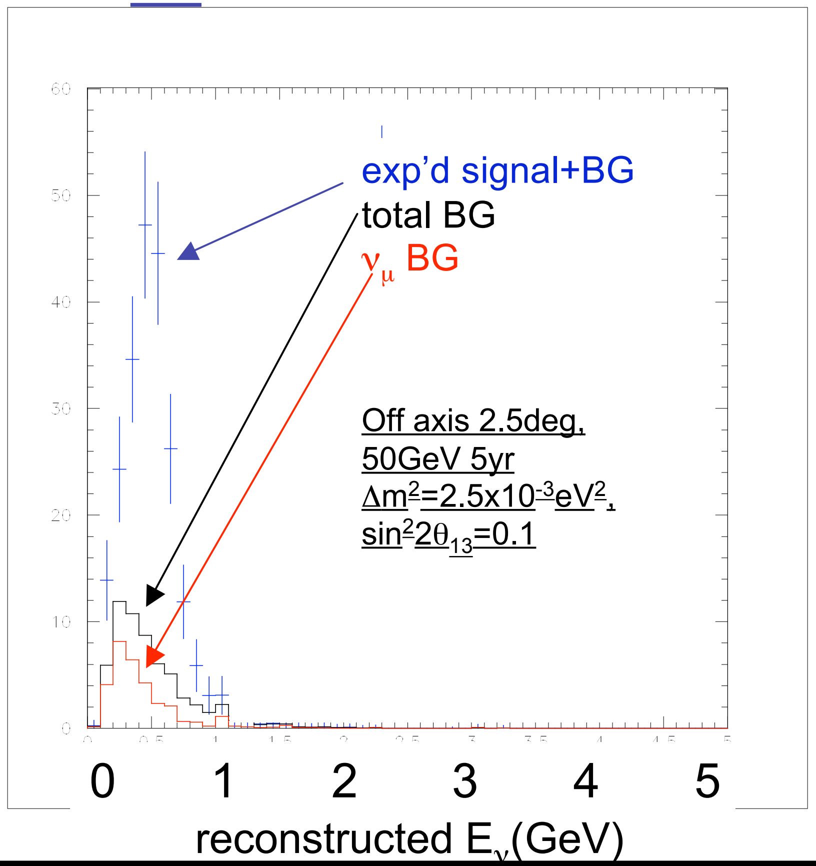


The best position is OA2.0~2.3deg

sensitivities for $\sin^2 2\theta_{13}$

Preliminary



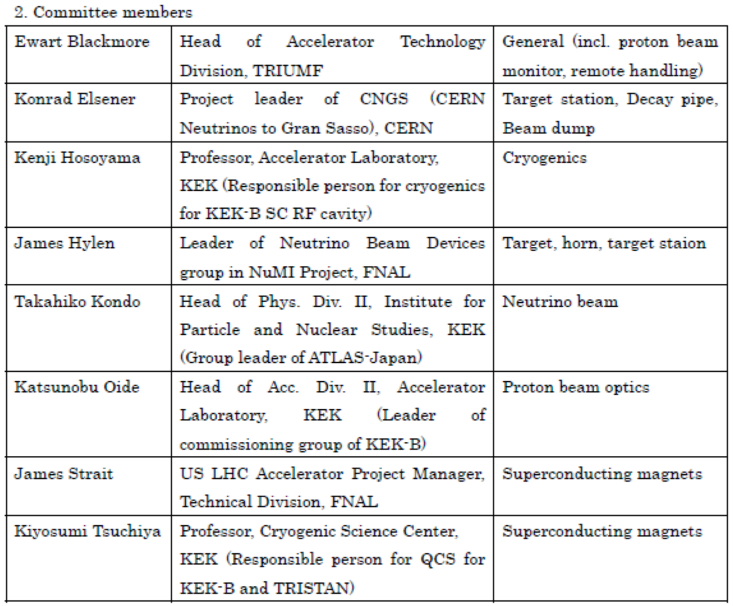


$\sin^2 2\theta_{13}$	ν_μ(CC+NC)	Bean ν_e	Osc'd ν_e	Signal+BG
● 0.1	10	13	103	126
● 0.01	10	13	10	33

(OA 2.5deg, 50GeV 5yr)

1^{st} technical advisory committee (ν-TAC)

- Nov. 12,13, 2003 (Just before approval)
- E.Blackmore (Chair,TRIUMF)
- Experts from NuMI/CNGS, SCmags/cryo., accelerator, remote handling
- Reviewed
  - Beam line concept
  - Conceptual design of all beamline components
  - Extensive review on SCmag (since most advanced, schedule pressed)
- Executive summary said
  - The committee feels that there are no "show stoppers" in terms of meeting the design goals for 0.75 MW operation.
  - A time frame of 5 years for the completion of the neutrino facility is a realistic goal.



2. Committee members

Ewart Blackmore	Head of Accelerator Technology Division, TRIUMF	General (incl. proton beam monitor, remote handling)
Konrad Elsener	Project leader of CNGS (CERN Neutrinos to Gran Sasso), CERN	Target station, Decay pipe, Beam dump
Kenji Hosoyama	Professor, Accelerator Laboratory, KEK (Responsible person for cryogenics for KEK-B SC RF cavity)	Cryogenics
James Hylen	Leader of Neutrino Beam Devices group in NuMI Project, FNAL	Target, horn, target staion
Takahiko Kondo	Head of Phys. Div. II, Institute for Particle and Nuclear Studies, KEK (Group leader of ATLAS-Japan)	Neutrino beam
Katsunobu Oide	Head of Acc. Div. II, Accelerator Laboratory, KEK (Leader of commissioning group of KEK-B)	Proton beam optics
James Strait	US LHC Accelerator Project Manager, Technical Division, FNAL	Superconducting magnets
Kiyosumi Tsuchiya	Professor, Cryogenic Science Center, KEK (Responsible person for QCS for KEK-B and TRISTAN)	Superconducting magnets

2nd ν-TAC

- Apr. 26~28, 2005
- Similar members, + Dynamic stress expert
- Timing when R&D & design are well advanced and being finalized
- All components reviewed, w/ major concern on
  - Thermal stress analysis,
  - Maintenance scenario

2nd (Apr.26, 2005)

Committee members

Ewart Blackmore (Chair) ewb@triumf.ca	Head of Accelerator Technology Division, TRIUMF	General (incl. proton beam monitor, remote handling)
Konrad Elsener Konrad.Elsener@cern.ch	Project leader of CNGS (CERN Neutrinos to Gran Sasso), CERN	Target station, Decay pipe, Beam dump
Kenji Hosoyama Kenji.Hosoyama@kek.jp	Professor, Accelerator Laboratory, KEK (Responsible person for cryogenics for KEK-B SC RF cavity)	Cryogenics
James Hylen hylen@fnal.gov	Leader of Neutrino Beam Devices group in NuMI Project, FNAL	Target, Horn, Target staion
Takahiko Kondo Taka.Kondo@kek.jp	Head of Phys. Div. II, Institute for Particle and Nuclear Studies, KEK (Group leader of ATLAS-Japan)	Neutrino beam
Clive Mark cmark@triumf.ca	Leader of Remote Handling Group, TRIUMF	Remote handling
Katsunobu Oide Katsunobu.Oide@kek.jp	Head of Acc. Div. II, Accelerator Laboratory, KEK (Leader of commissioning group of KEK-B)	Proton beam line
Peter Sievers Peter.Sievers@cern.ch	Professor, Accelerator Technology Department, CERN	Target, Horn
James Strait strait@fnal.gov	Head of Particle Physics Division, FNAL	Superconducting magnets