T2K phase-I and II

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Talk at session5 of WG1 at NUFACT05, June 23, 2005

Contents

- Introduction of T2K experiment
- Neutrino detectors
- ν_μ disappearance and ν_e appearance
- CP violation in T2K Phase-II

Long baseline oscillation

Maki-Nakagawa-Sakata (MNS) matrix $|\nu_l\rangle = \Sigma U_{li} |\nu_i\rangle$ $s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \boxed{e^{-i\delta}} \end{pmatrix} \cdot \boxed{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **Precise meas. of disappearance $\nu_\mu \rightarrow \nu_x$**

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

- **Discovery of $\nu_\mu \rightarrow \nu_e$ appearance**

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

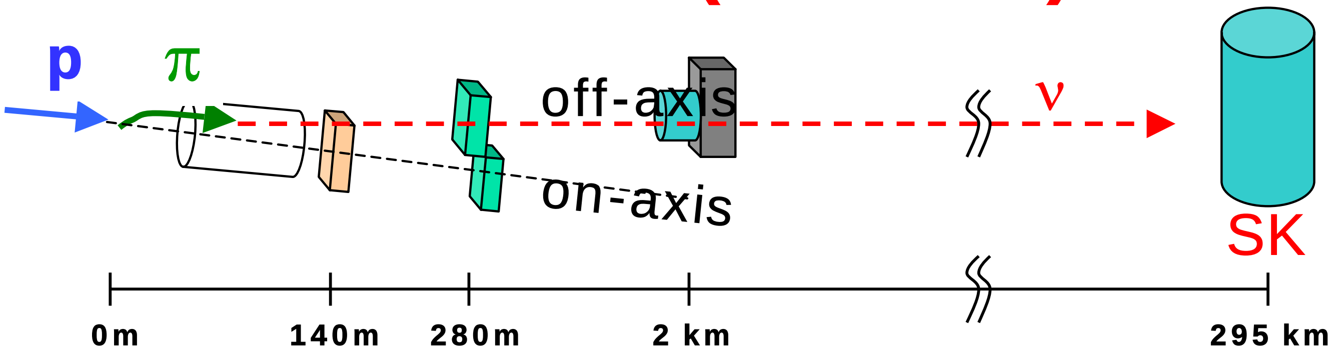
- **Discovery of CP violation (Phase2)**

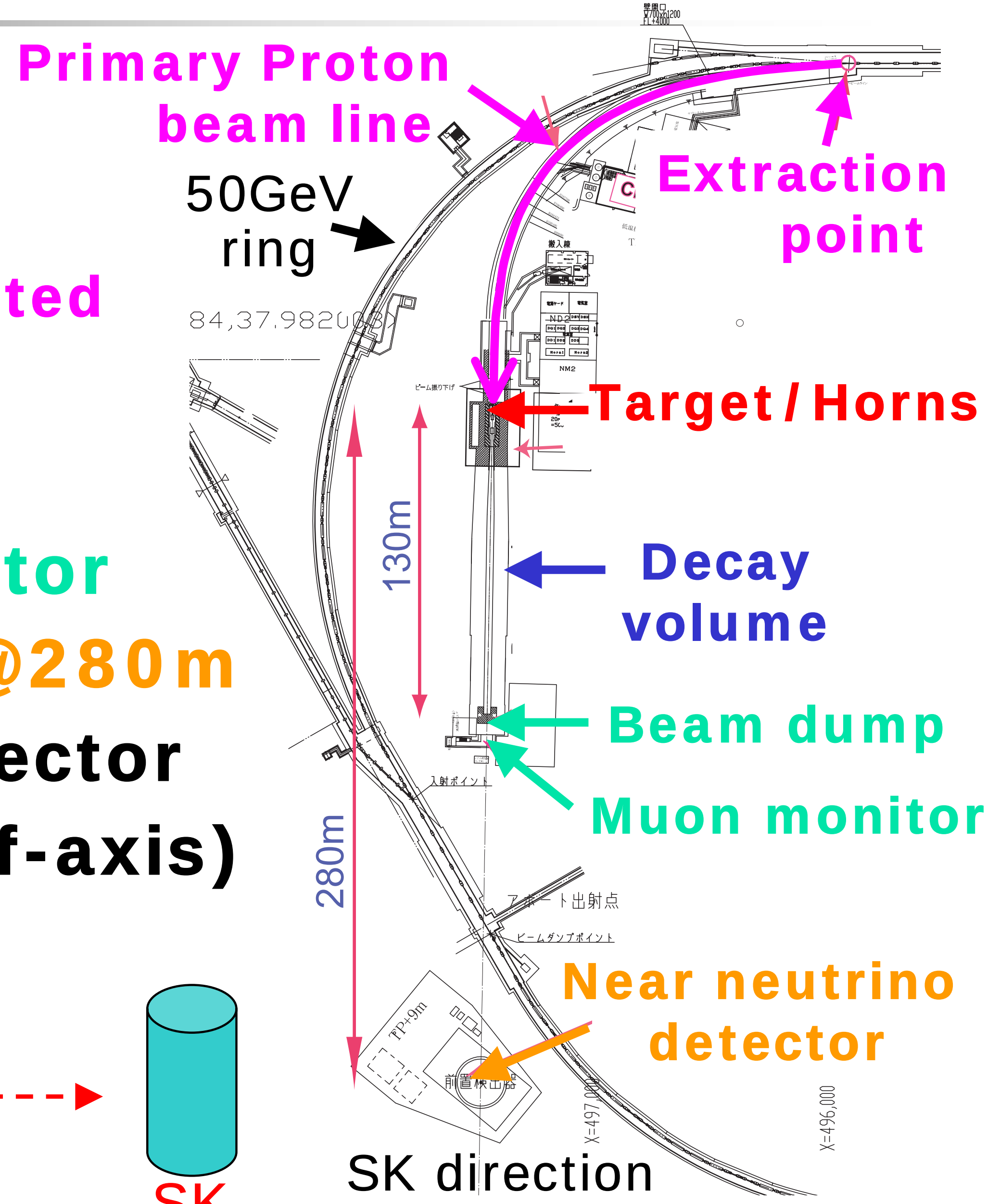
$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

J-PARC Neutrino facility

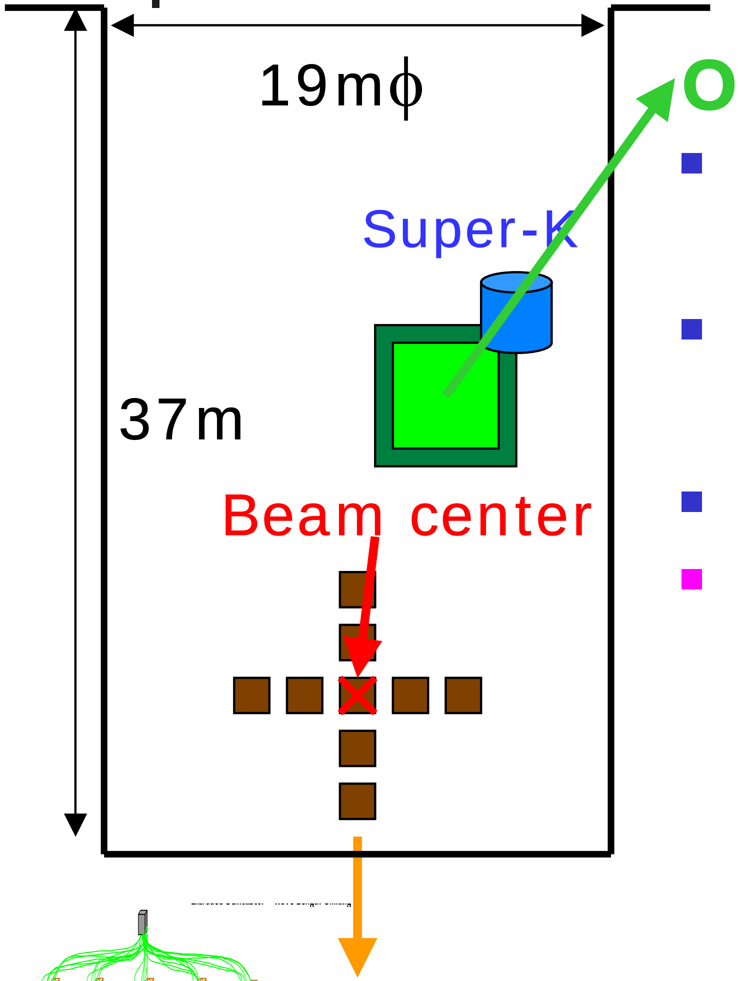
Components

- Primary proton beam line
  - 50GeV, 0.75MW, Fast extracted
- Target / Horns
- Decay volume (130m)
- Beam dump & Muon monitor
- Near neutrino detectors @280m
- Second near neutrino detector @2km: future option (Off-axis)
- Far detector SK (Off-axis)



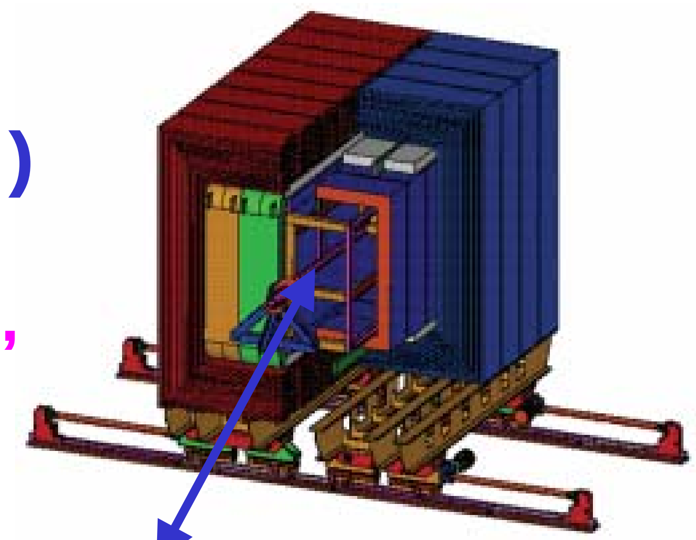


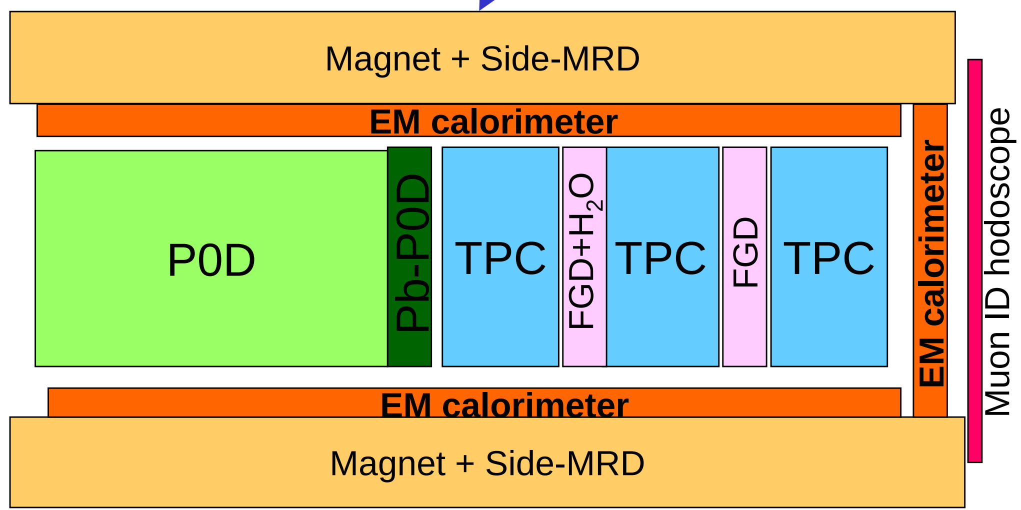
Near Detector @ 280m

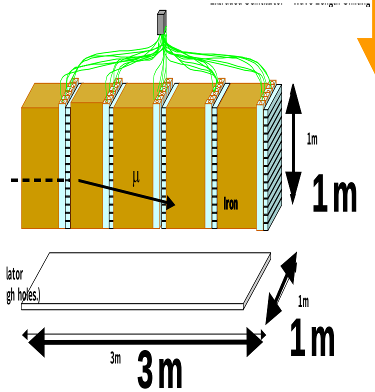


Off-axis (~2°)

- ν_μ and ν_e fluxes and spectra
- ν interaction study (CC-QE,non-QE,π^0,)
- Kaon contributions
- UA1 mag, FGD, TPC, Ecal,..







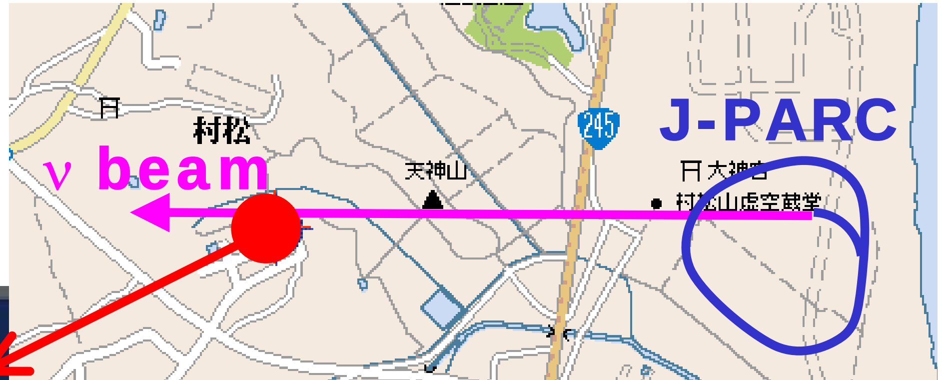
On-axis (0°)

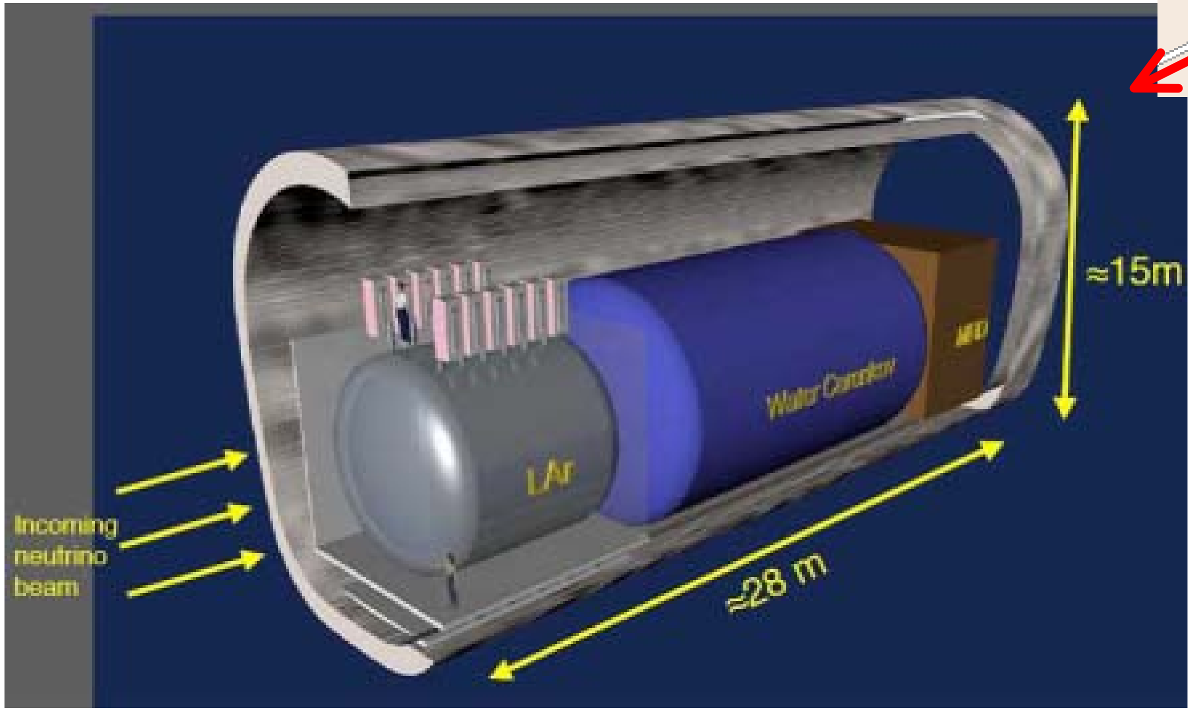
- Beam direction
- Grid layout

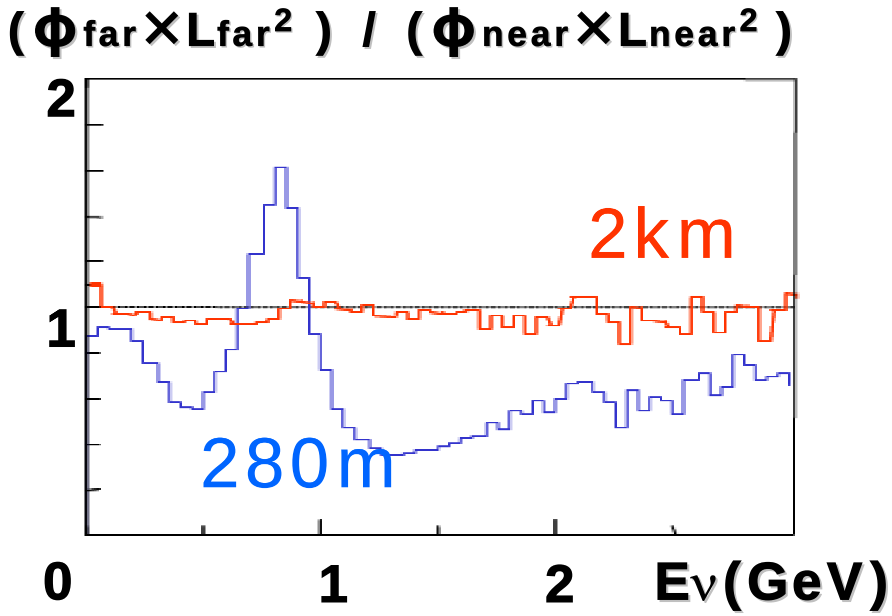
Near Detector @2km

Future option to reduce systematic errors

- ν_μ energy spectrum for ν_μ disappearance
- ν_e background study for ν_e appearance

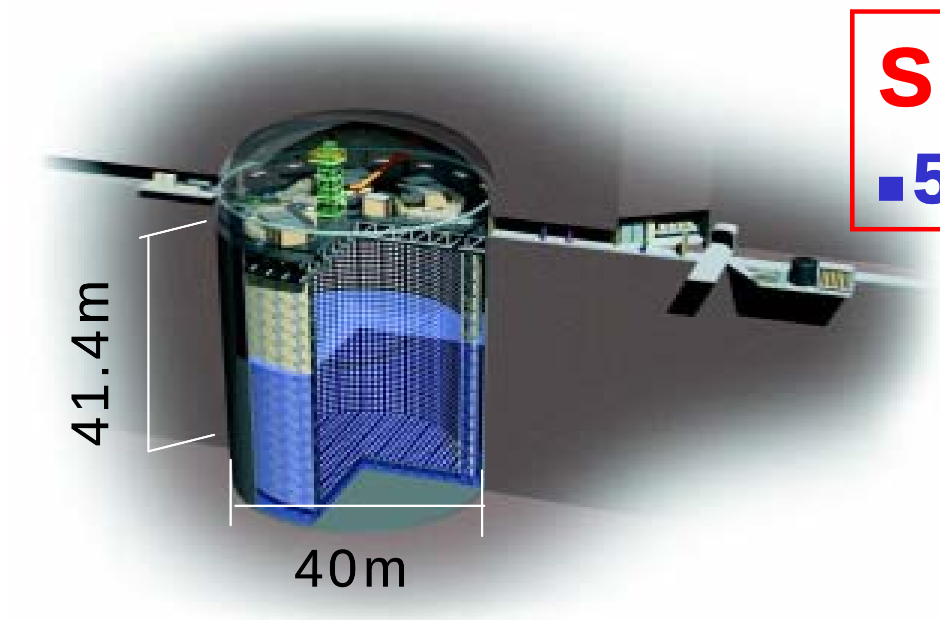






⇒ Next speaker

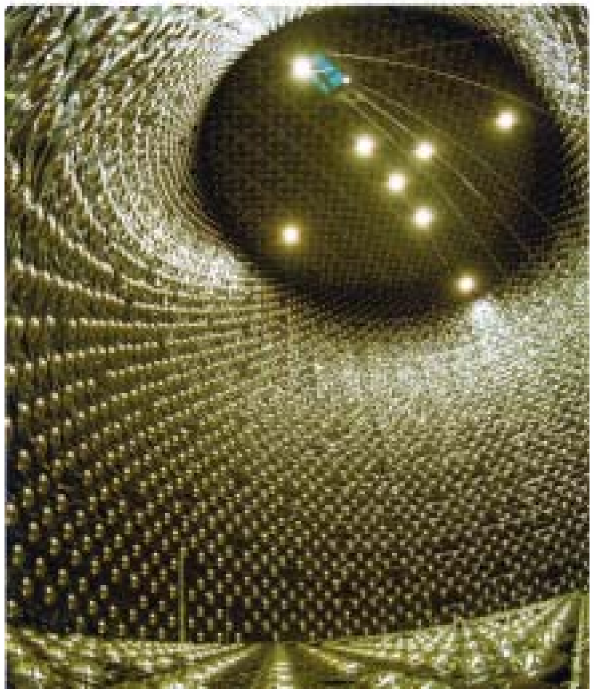
Far Detector: SK



Super-Kamiokande

- 50kt water Cherenkov

- Partial reconstruction in 2002
  - 47% of PMT's(~5200)
- Full reconstruction
  - PMT's attachment: Nov.2005 ~ Mar.2006
  - Water filling: Apr. ~ May 2006
  - Data taking: from June 2006

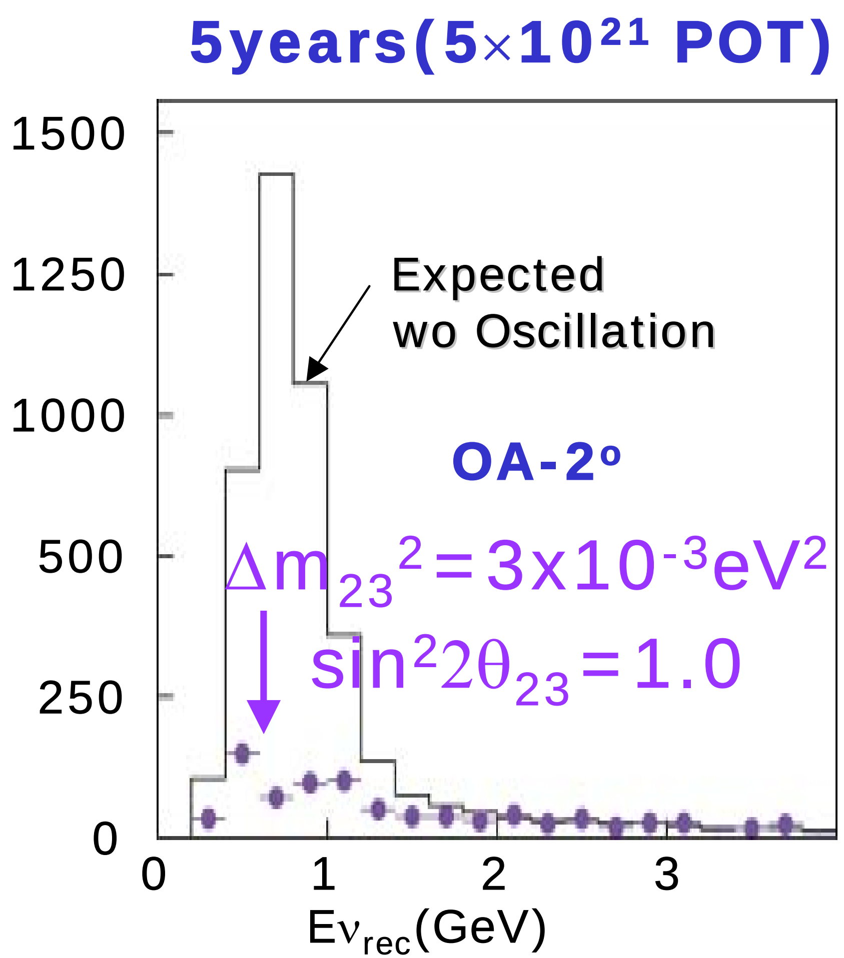


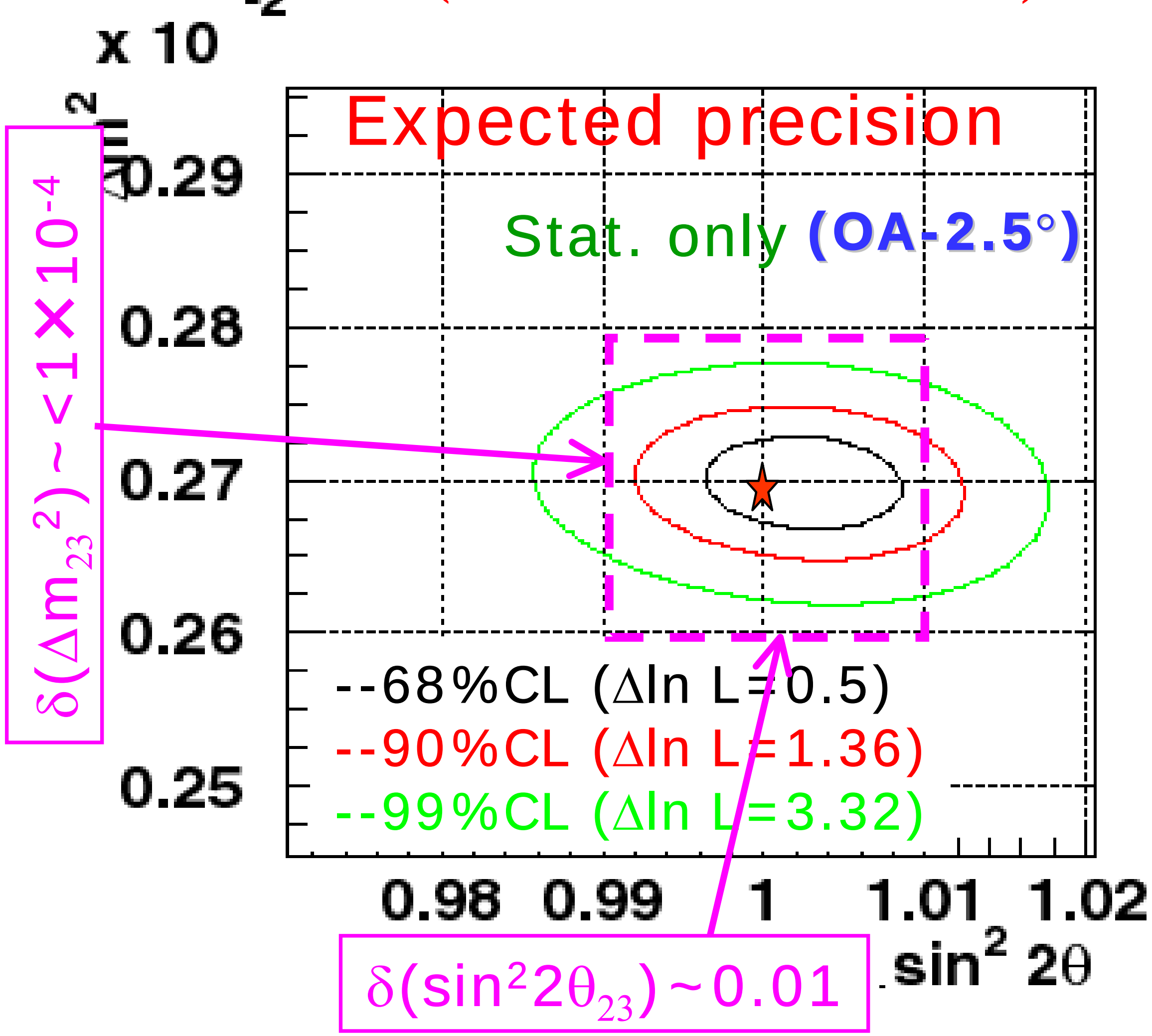
ν_μ disappearance

Precise measurement of θ_{23} & Δm_{23}

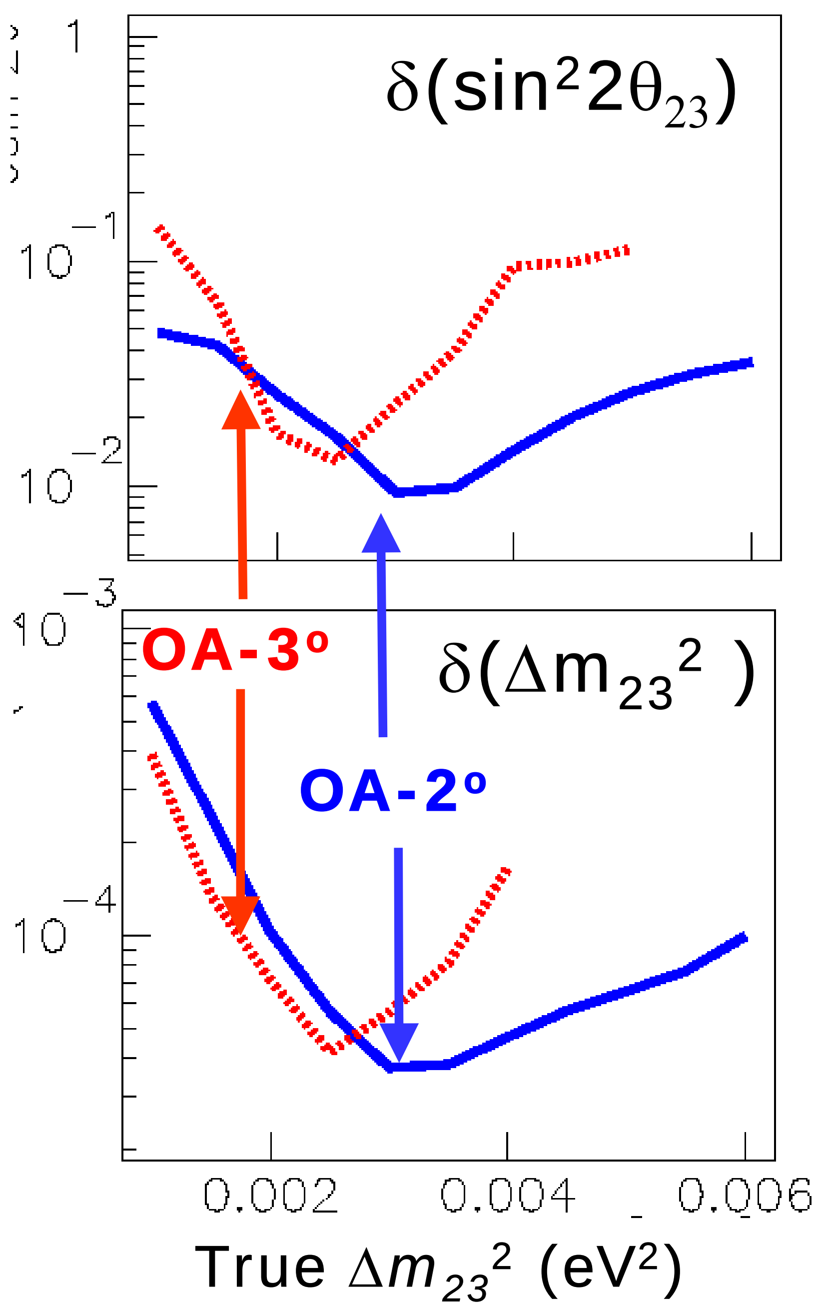
$\Delta m^2_{12} << \Delta m^2_{23} \approx \Delta m^2_{13}$

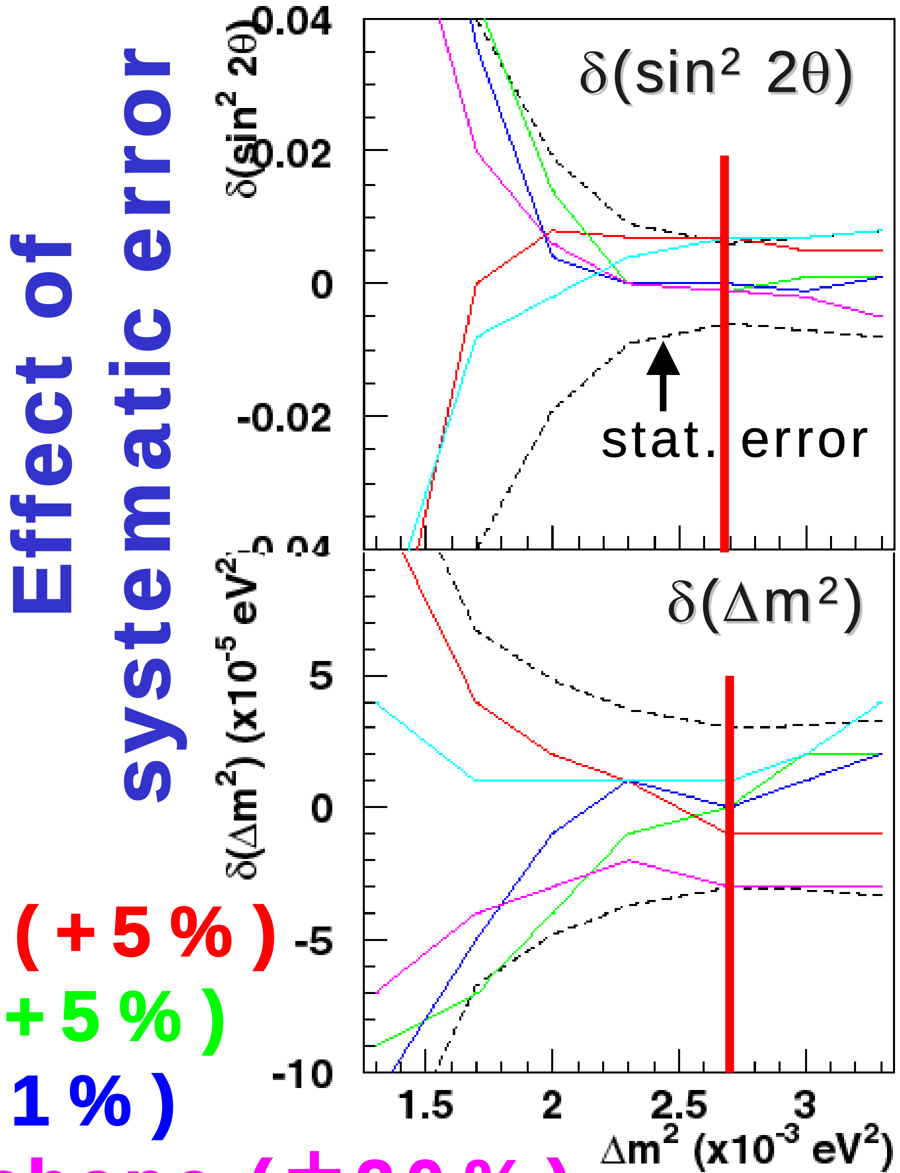
$$P_{\mu \to x} \approx 1 - \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} \cdot \sin^2 (1.27 \Delta m^2_{23} L / E_\nu)$$





Sensitivity on disappearance





- Norm. (+5%)
- NQE (+5%)
- E_{SK} (+1%)
- beam shape (±20%)
- beam width (5%)

Discovery of ν_e appearance

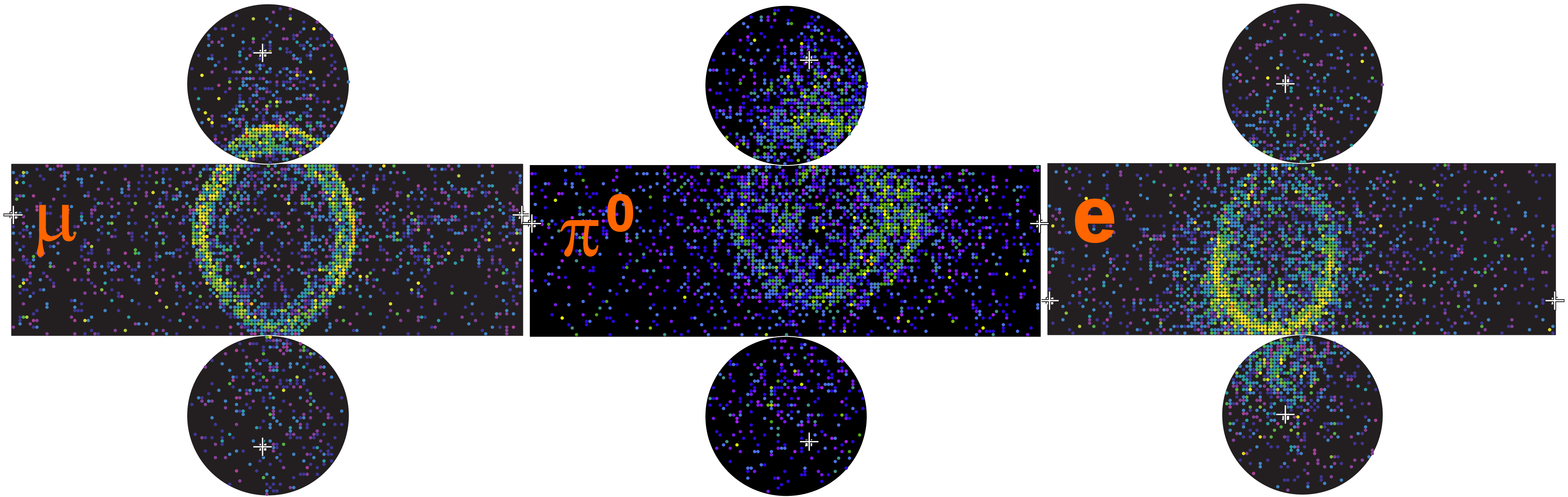
ν_e appearance: θ_{13} & Δm_{13}

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

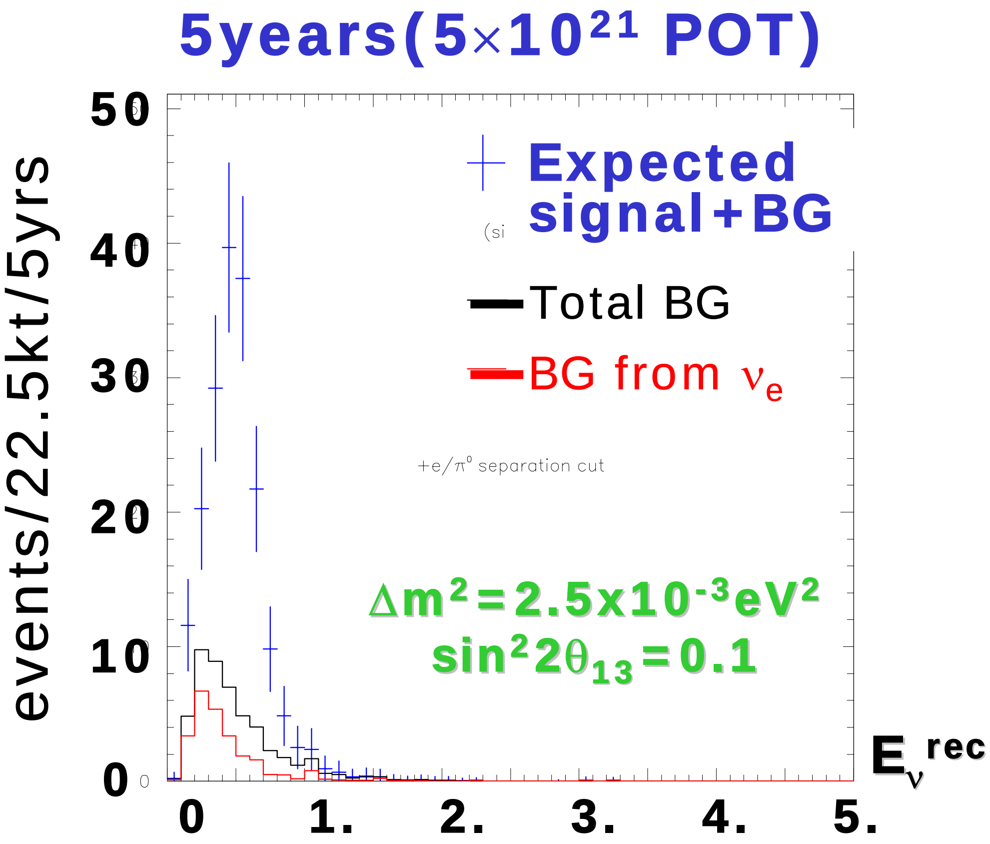
Background for ν_e appearance

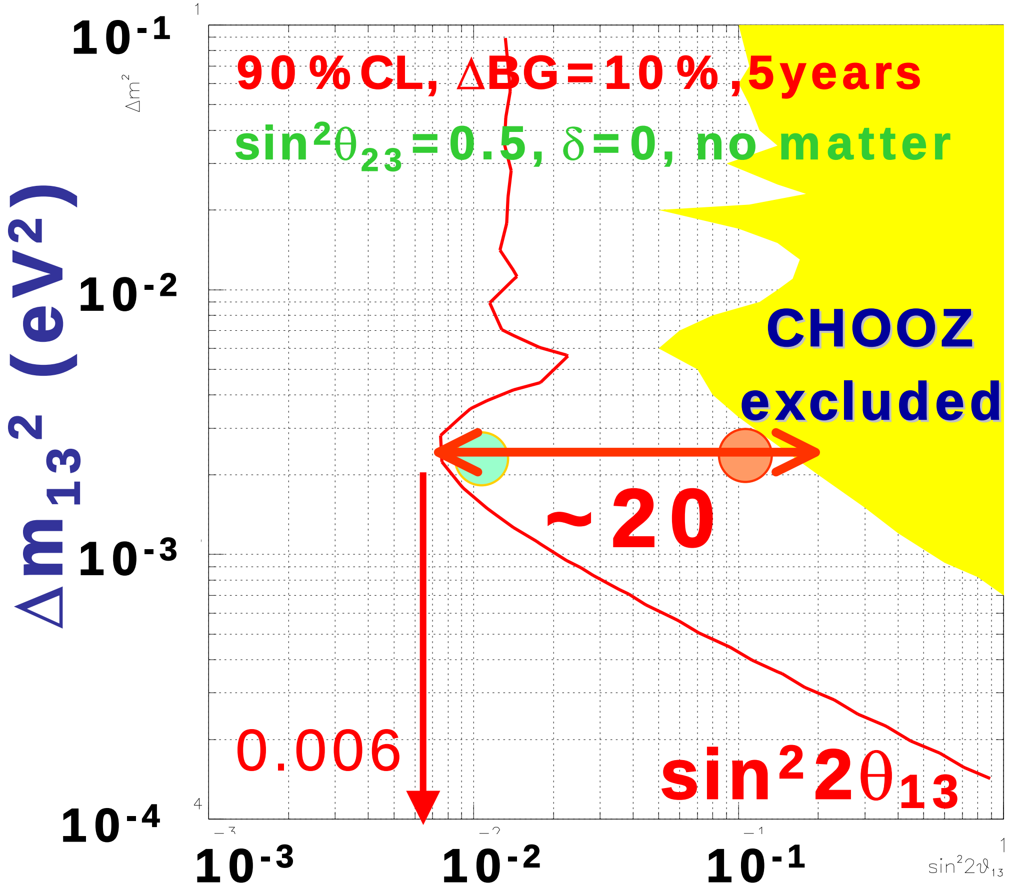
- Intrinsic ν_e component in initial beam
- Merged π^0 ring from ν_μ interactions

Requirement:10% uncertainty for BG estimation



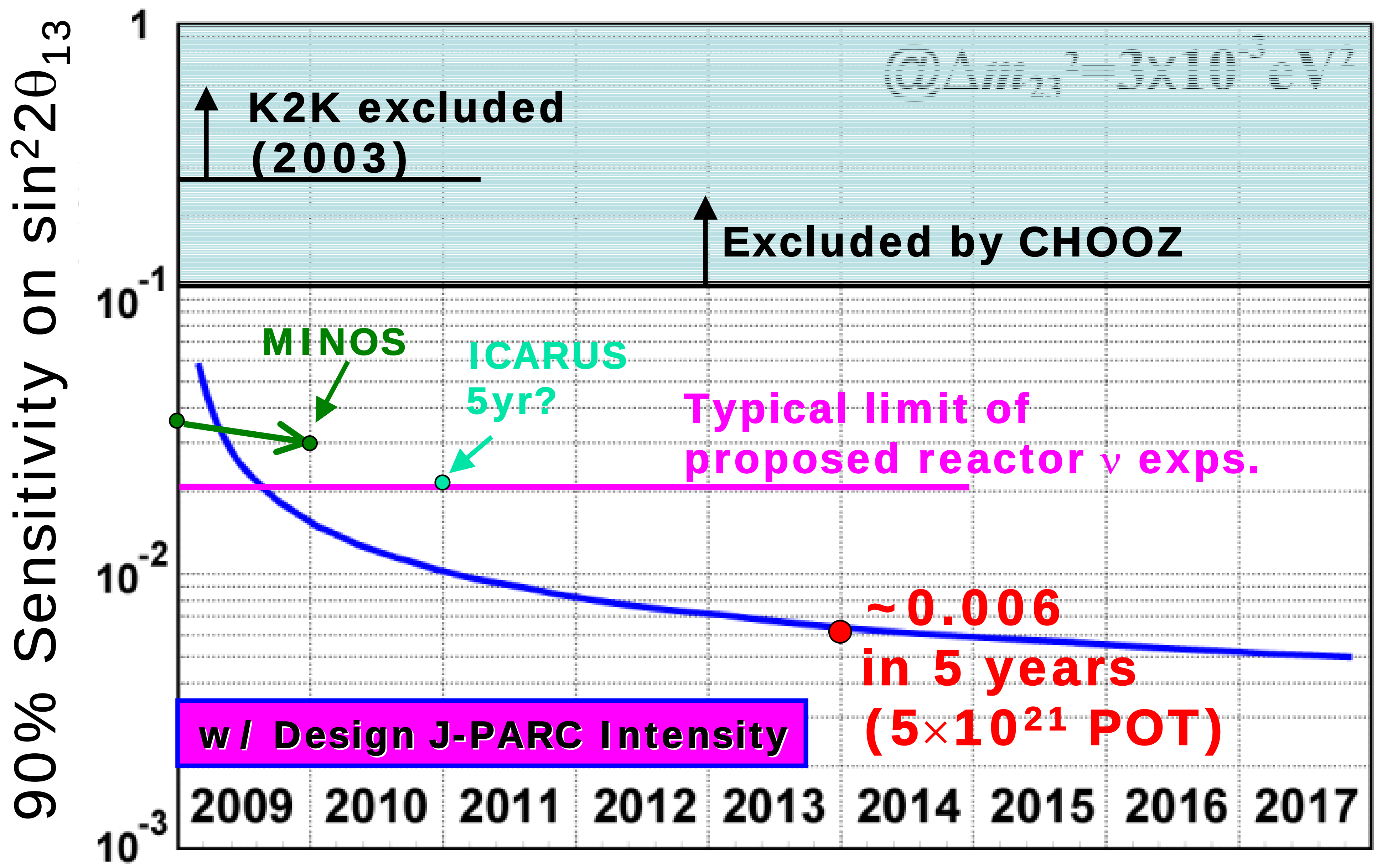
Sensitivity on appearance





$\sin^2 2\theta_{13}$	Background in Super-K			Signal	Signal + BG
	ν_μ	ν_e	total		
0.1	10	13	23	103	126
0.01				10	33

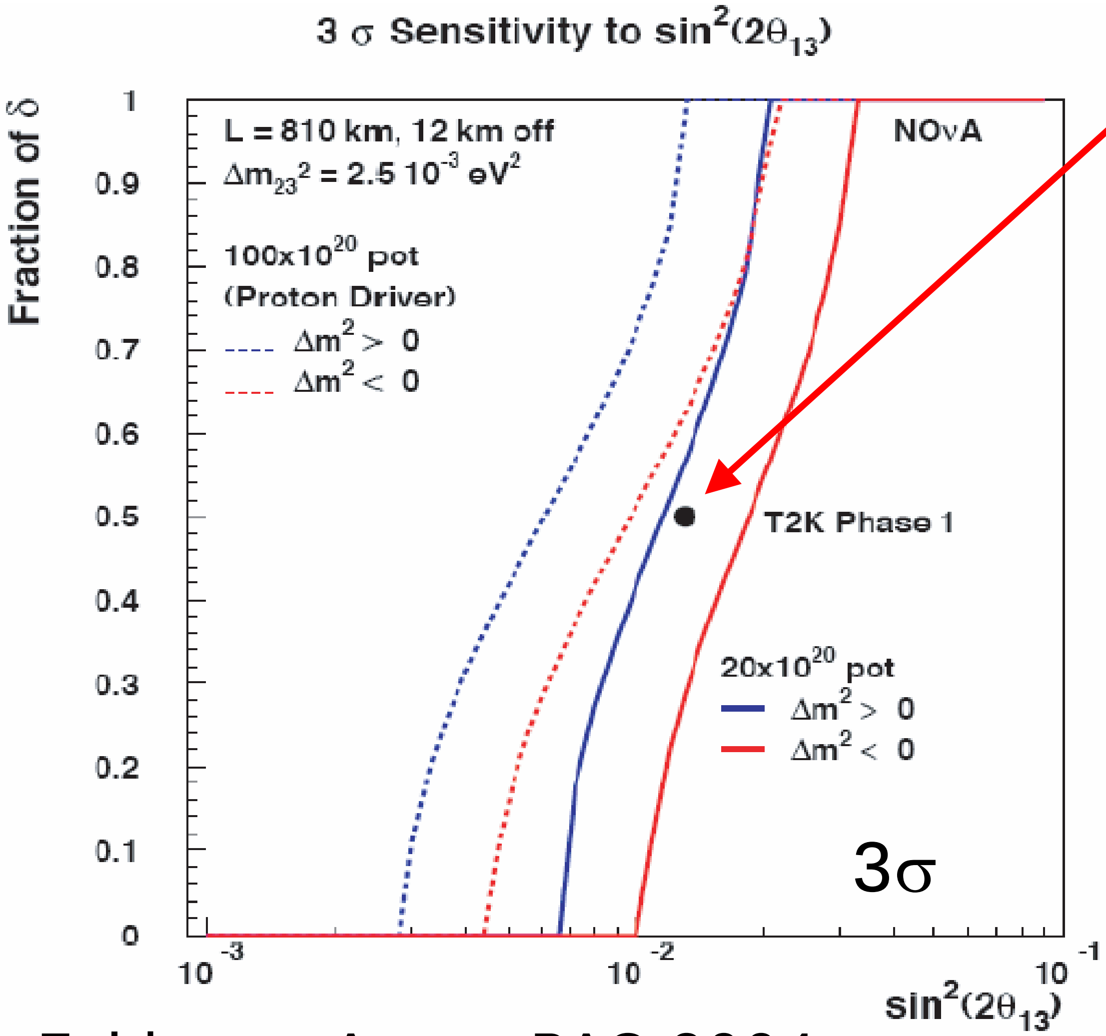
Development of sensitivity

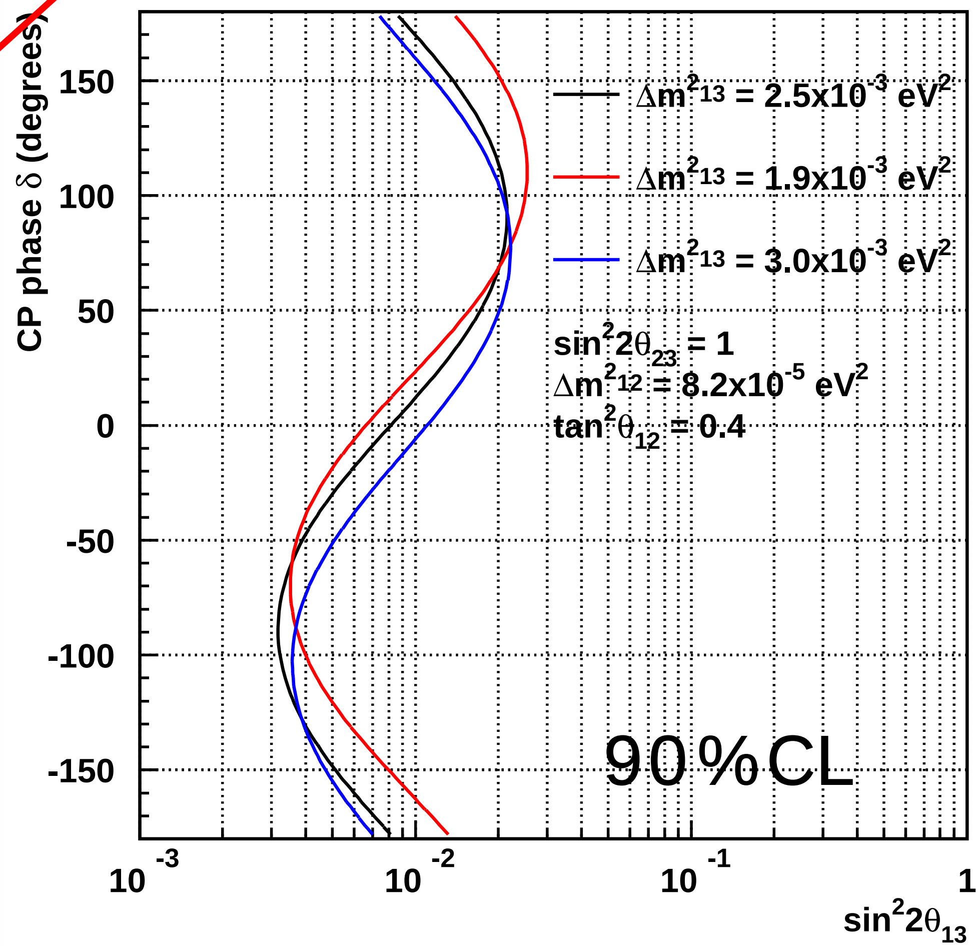


Comparison with NOνA

NOνA: 20×10^{20} or 100×10^{20}
with 50kton baseline detector

T2K-I:50×10^{20} POT





Feldman, Aspen PAC 2004

T2K phase-II

x~100 sensitivity for CP violation

- **J-PARC: 0.75MW ⇒ 4MW (x5)**
- **SK:22.5kton ⇒ HK:0.54Mton (x24)**

CP violation in lepton sector

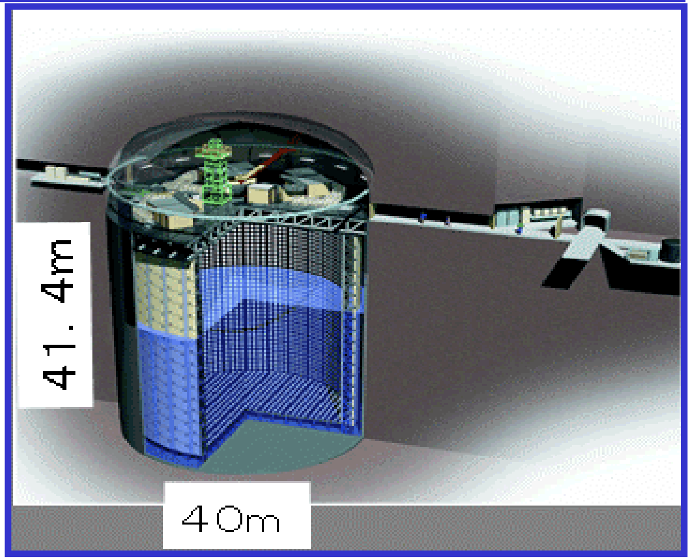
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \approx \frac{\Delta m_{12}{}^2 L}{4E_\nu} \bullet \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \bullet \boxed{\sin\delta}$$

Maki-Nakagawa-Sakata (MNS) matrix $|\nu_l\rangle = \Sigma U_{li} |\nu_i\rangle$ $s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \boxed{e^{-i\delta}} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

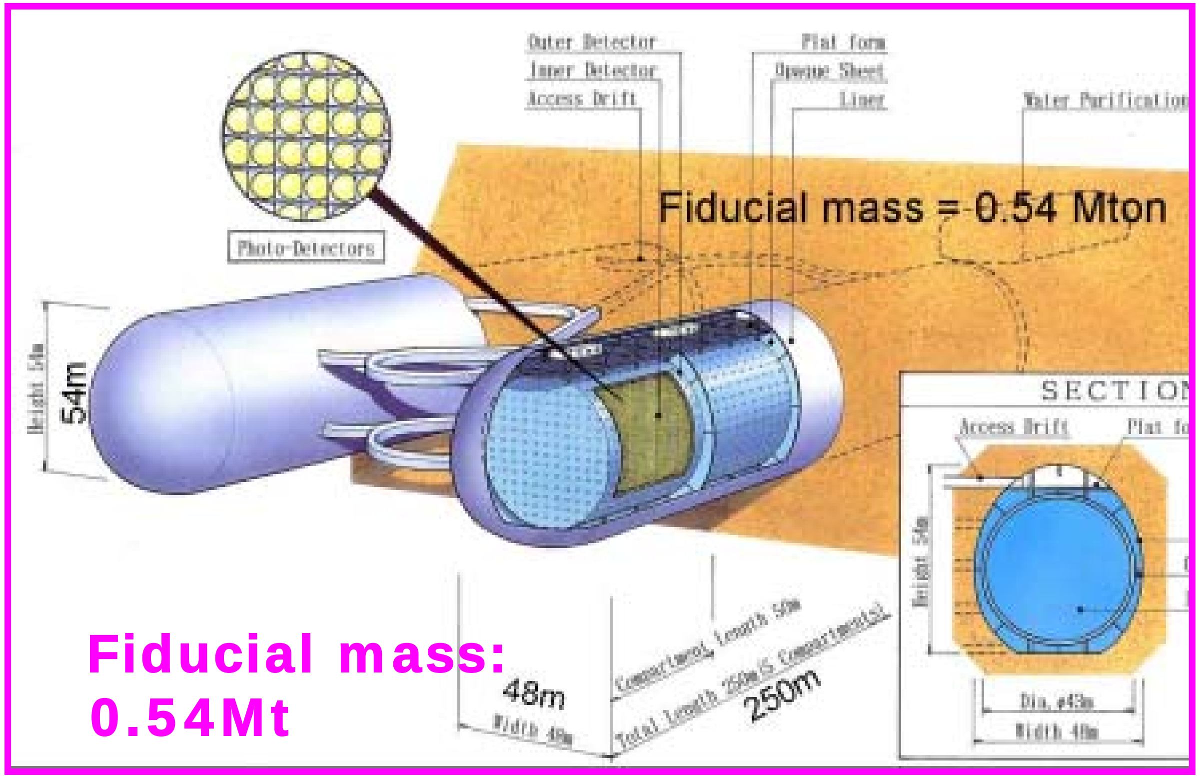
Hyper-Kamiokande

Super-Kamiokande
(50kt, 11000 PMT's)



Fiducial mass: 22.5kt

Hyper-Kamiokande
(~1Mt,～200000 photo-sensors)



Fiducial mass: 0.54Mt

• **Not official, Not approved**

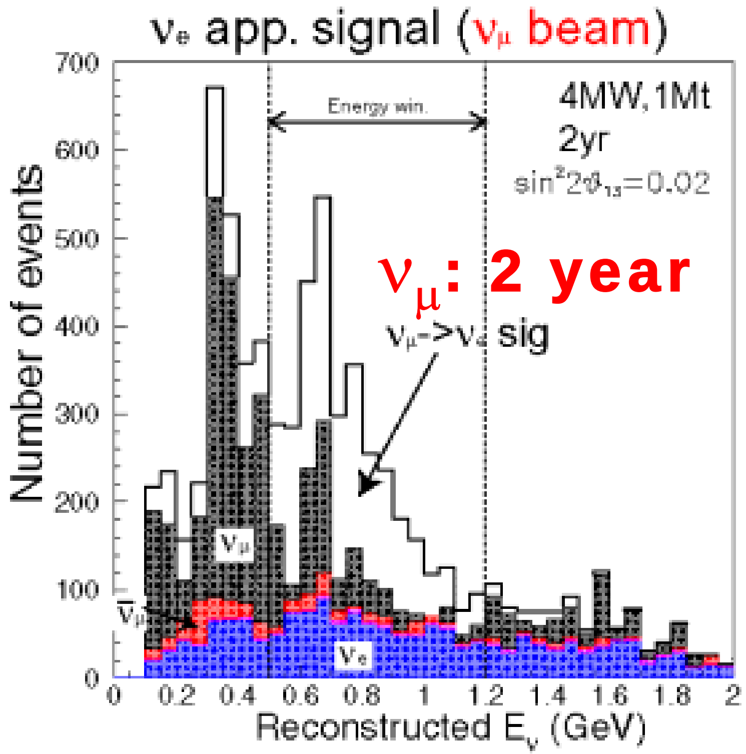
2008	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23

T2K-I

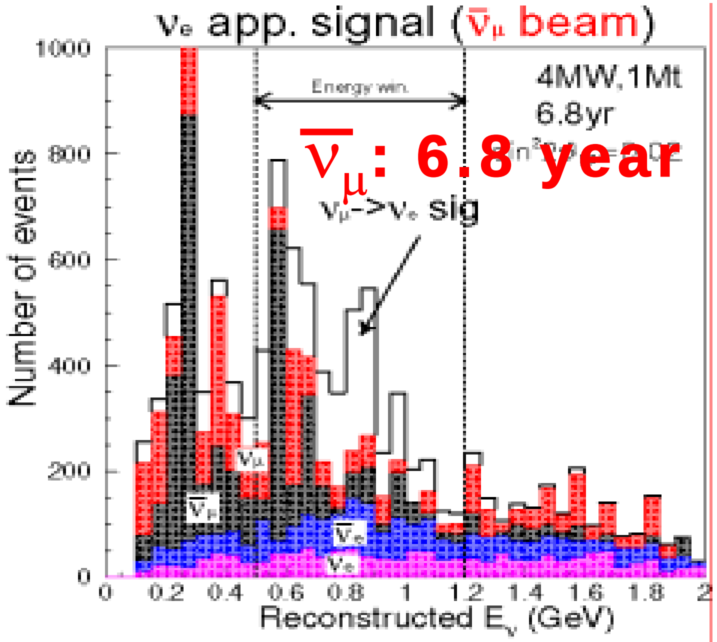
HK construction
(7~10 years)

T2K-II

Expected signal and BG



Very Preliminary



$\sin^2 2\theta_{13}=0.02$

4MW, 540kt

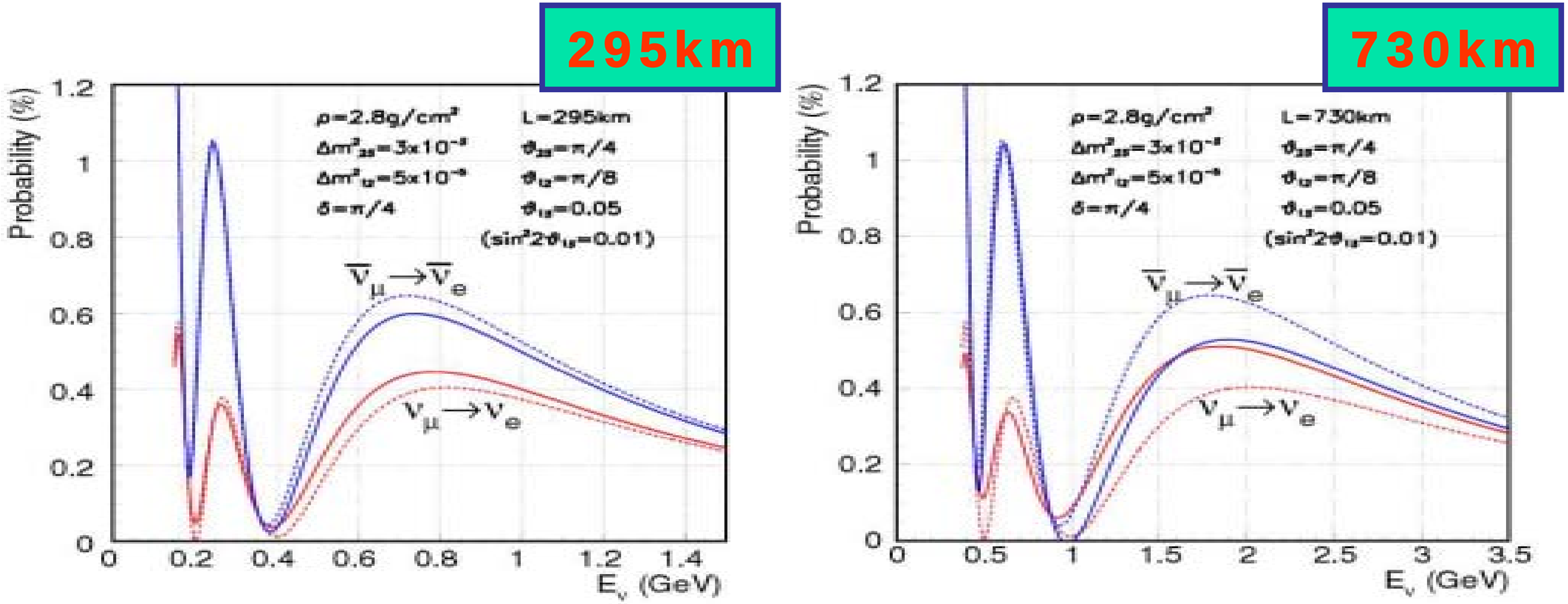
$\Delta m_{21}^2=6.9\times10^{-5}\mathrm{eV}^2$
$\Delta m_{32}^2=2.8\times10^{-3}\mathrm{eV}^2$
$\theta_{12}=0.594$
$\theta_{23}=\pi/4$

$\sin^2 2\theta_{13}=0.01$

	signal		background				
	$\delta=0$	$\delta=\pi/2$	total	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
$\nu_\mu \to \nu_e$	536	229	913	370	66	450	26
$\bar{\nu}_\mu \to \bar{\nu}_e$	536	790	1782	399	657	297	430

CPV vs matter effect

$\nu_\mu \rightarrow \nu_e$ osc. probability w/ CPV/matter



@$\sin^2 2\theta_{13}$=0.01

J-PARC/T2K: smaller distance/lower energy

small matter effect

$\Rightarrow$Pure CPV & Less sensitivity on sign of Δm^2

3σ Sensitivity for CPV

$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

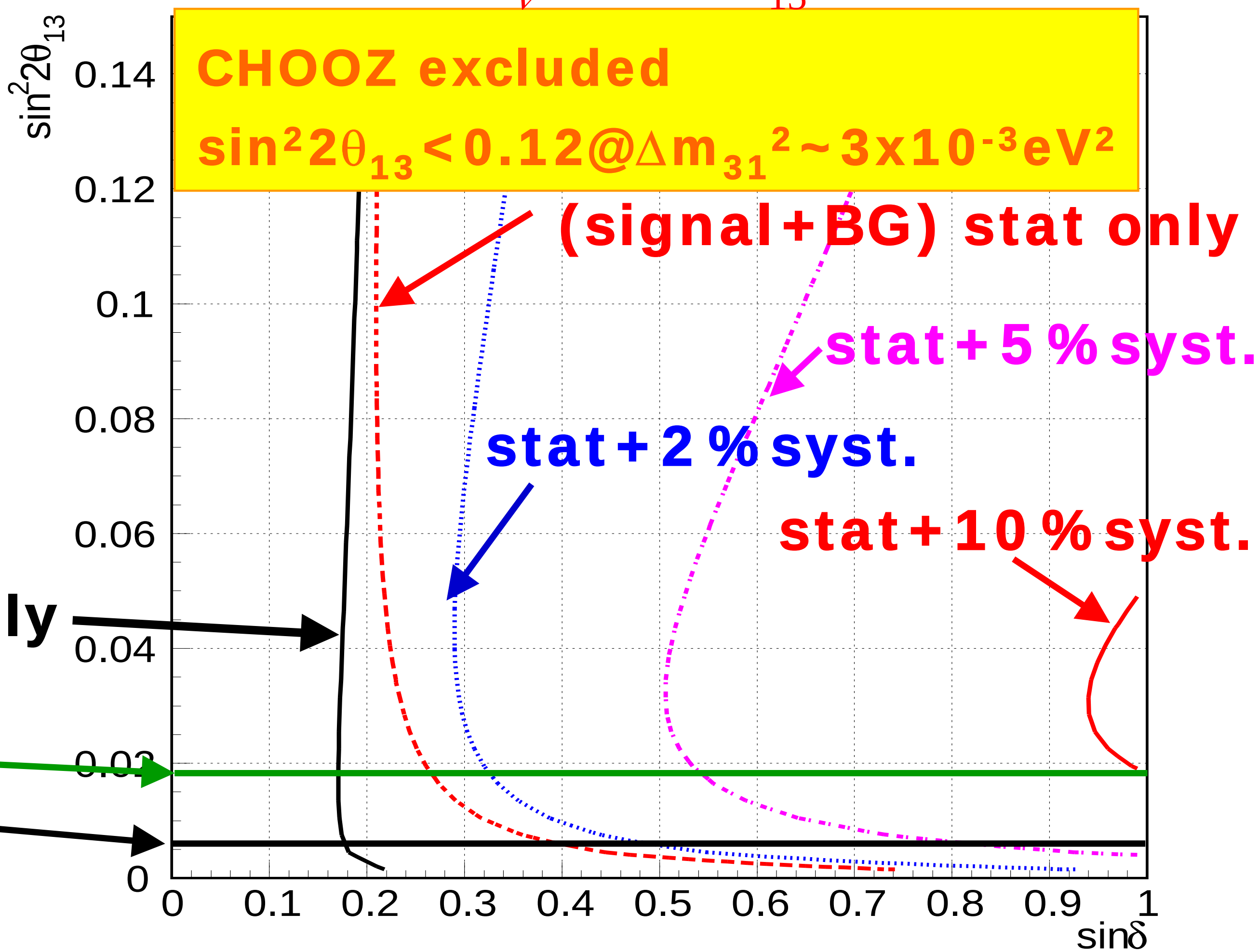
- 4MW, 540kt
- 2yr for ν_μ
- 6.8yr for $\overline{\nu}_\mu$

$\Delta m_{21}^2 = 6.9\times10^{-5}\,\mathrm{eV}^2$
$\Delta m_{32}^2 = 2.8\times10^{-3}\,\mathrm{eV}^2$
$\theta_{12} = 0.594$
$\theta_{23} = \pi/4$

no BG,signal stat only

T2K-I 3σ

T2K-I 90%



3σ CP sensitivity : $|\delta| > 20^\circ$

for $\sin^2 2\theta_{13} > 0.01$ with 2% syst.

Summary

- T2K-I experiment will start in 2009
  After five years run or 5×10^{21} POT,
  - ν_μ disappearance
    $\delta(\sin^2 2\theta_{23}) \sim 0.01$, $\delta(\Delta m_{23}^2) \sim <1\times10^{-4}$
  - Discovery of $\nu_\mu \rightarrow \nu_e$ appearance
    $\sin^2 2\theta_{13} > 0.006$
- Future upgrade as T2K phase-II
  4MW beam and Hyper-Kamiokande
  to discover CP violation

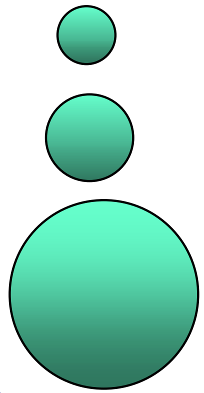
supplement

Neutrino oscillation

If neutrinos are massive,

Weak eigenstates ν_e, ν_μ, ν_τ

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{MNS} V^{CP}_{M} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

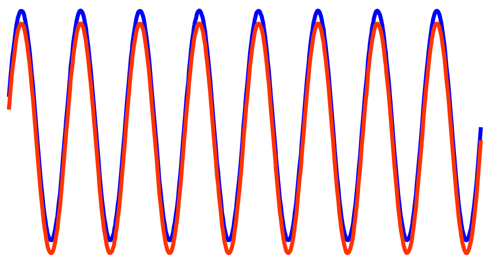


m $_1$ **m** $_2$ **m** $_3$ **Mass eigenstates**

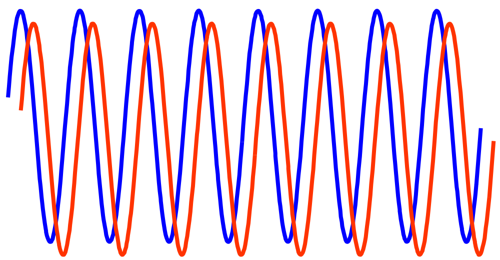
$$U_{MNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & +c_{23} & +s_{23}\\ 0 & -s_{23} & +c_{23}\end{pmatrix}\begin{pmatrix}+c_{13} & 0 & +s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & +c_{13}\end{pmatrix}\begin{pmatrix}+c_{12} & +s_{12} & 0\\ -s_{12} & +c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

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

$$V^{CP}_{M} = \begin{bmatrix} e^{i\alpha_1} & 0 & 0\\ 0 & e^{i\alpha_2} & 0\\ 0 & 0 & 1\end{bmatrix}$$



L~295km



$\nu_\mu \rightarrow \nu_\tau$, ν_e
Oscillation

$$|\nu_\alpha\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta \Longrightarrow |\nu_1\rangle\, e^{-i\frac{m_1^2}{2E}L} \cos\theta + |\nu_2\rangle\, e^{-i\frac{m_2^2}{2E}L} \sin\theta$$

$\alpha = e, \mu, \tau$ $\quad m_1 < m_2$

$$= |\nu_\alpha\rangle\left(1 - \sin^2 2\theta \sin^2(\Delta m^2 \frac{L}{4E})\right) + |\nu_\beta\rangle \sin^2 2\theta \sin^2(\Delta m^2 \frac{L}{4E})$$

More exact oscillation probability

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

θ_{13}

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

CP conserving

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

$\boxed{\cancel{CP}}$

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

solar ν

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

matter effect

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

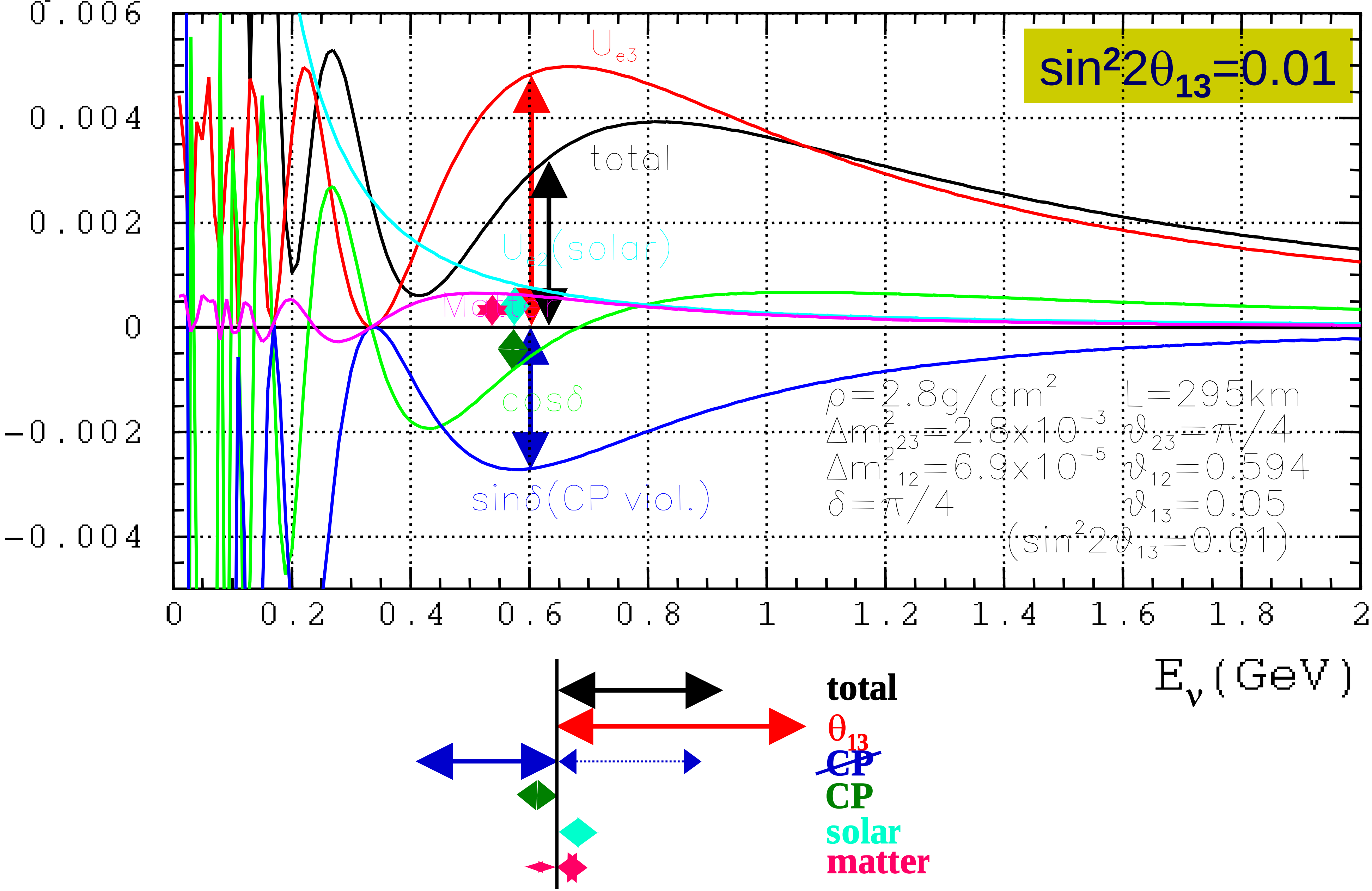
$\Phi_{ij} = \Delta m_{ij}^2 L / 4E$, $\quad S_{ij} = \sin\theta_{ij}$, $C_{ij} = \cos\theta_{ij}$

L : flight length, E : neutrino energy,

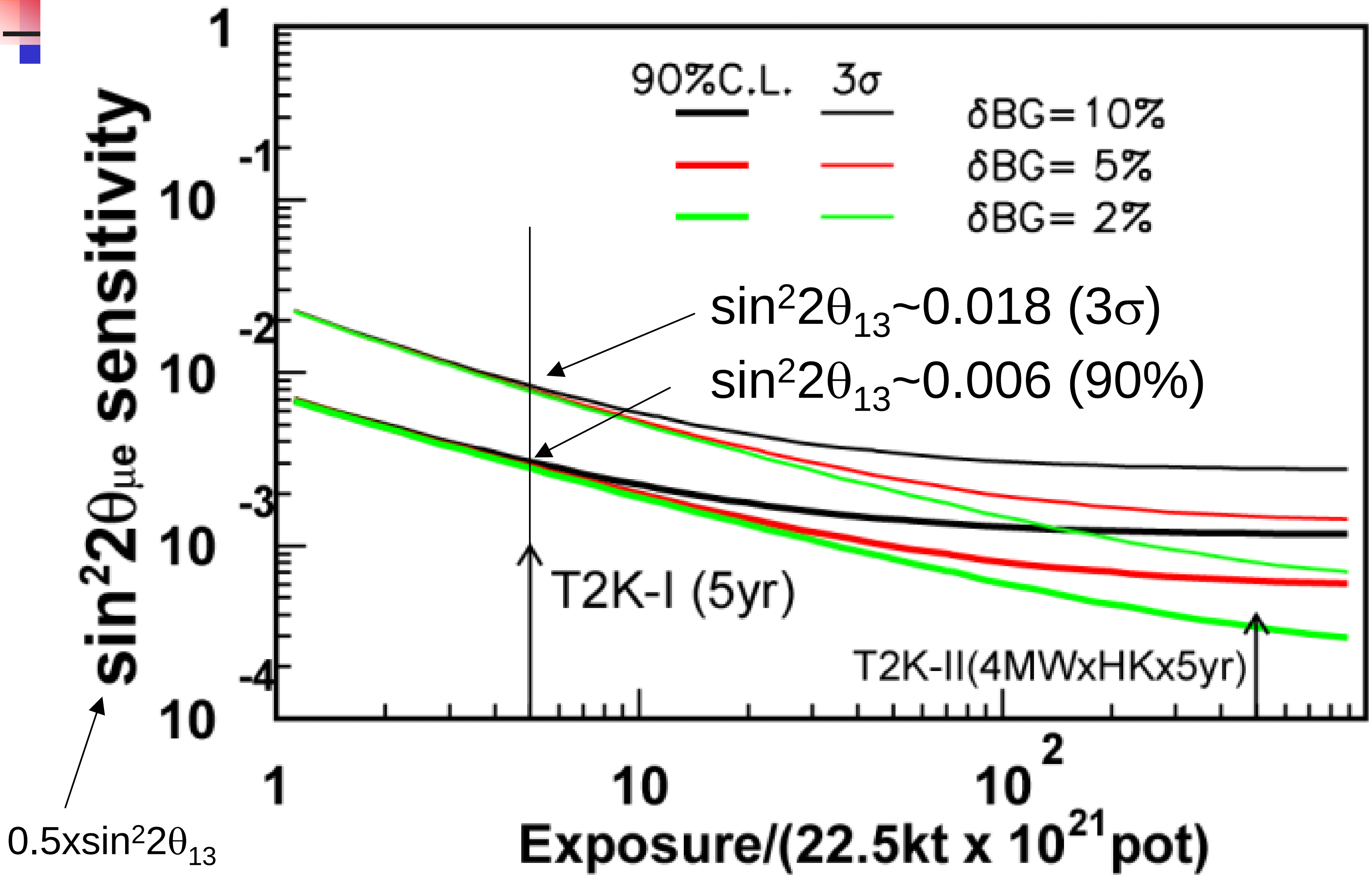
$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$, $\quad m_i$: mass eigenvalues

$$a = 7.6 \times 10^{-5} \left(\frac{\rho}{[g/cm^3]}\right)\left(\frac{E}{[GeV]}\right) \quad [\mathrm{eV}^2]$$

$\nu_\mu \rightarrow \nu_e$ oscillation probability



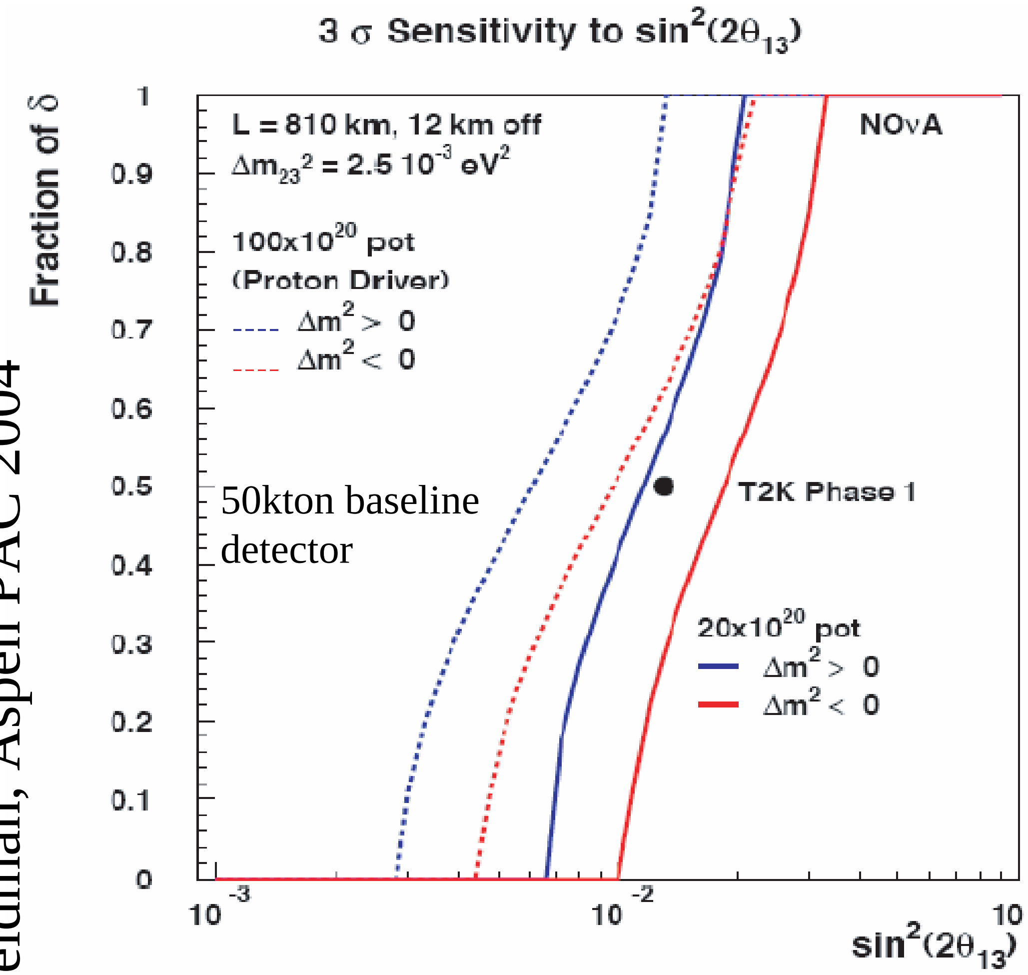
Sensitivity for Mixing Angle



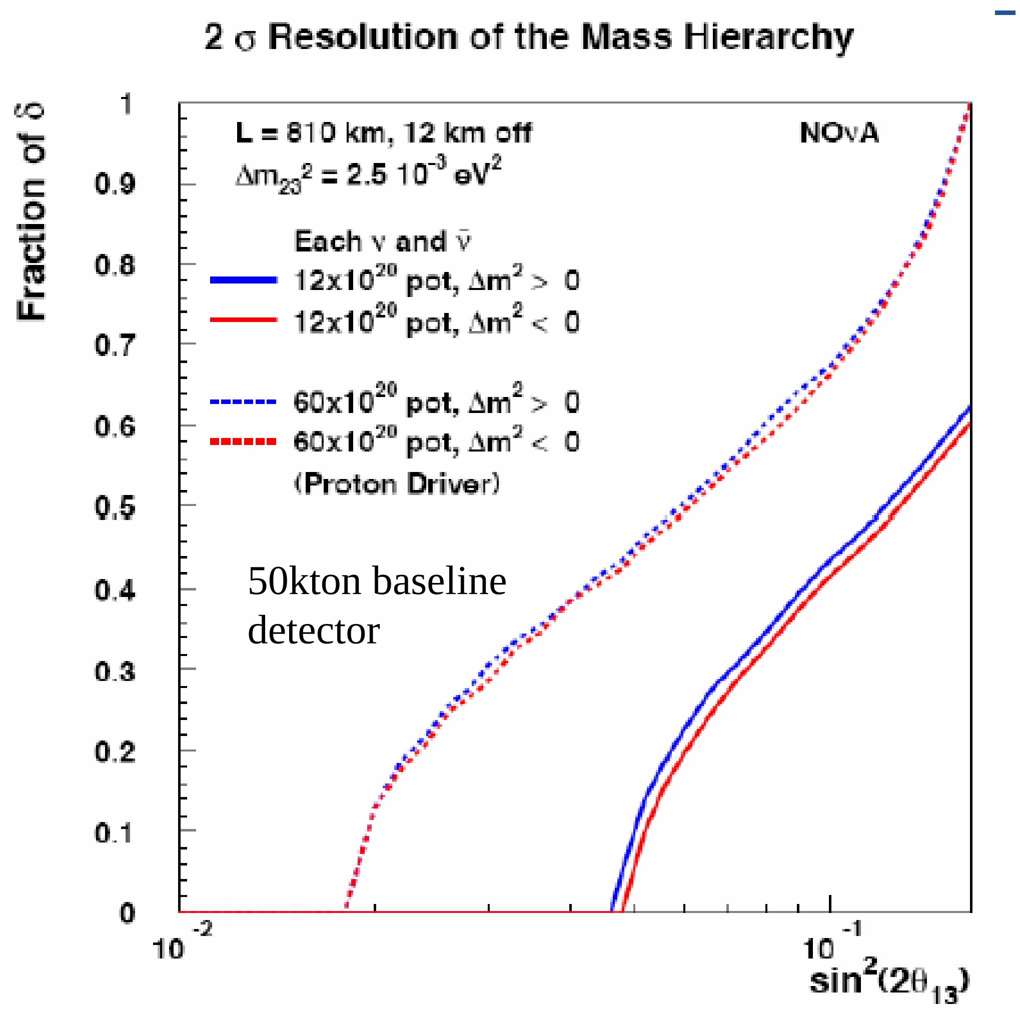
Background systematic error required to be ~ less than 10%

NOνA Physics Reach

ν_e appearance

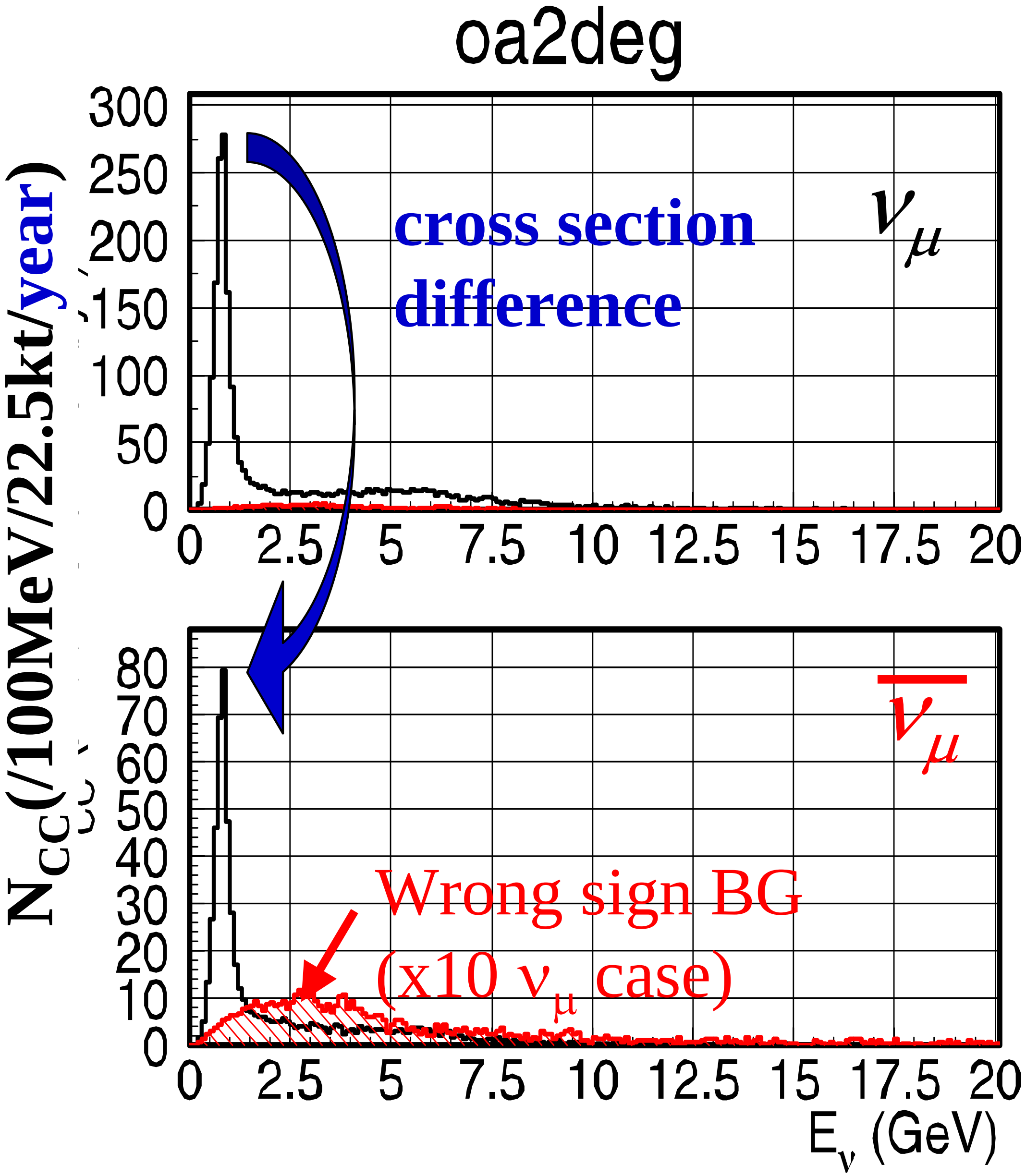


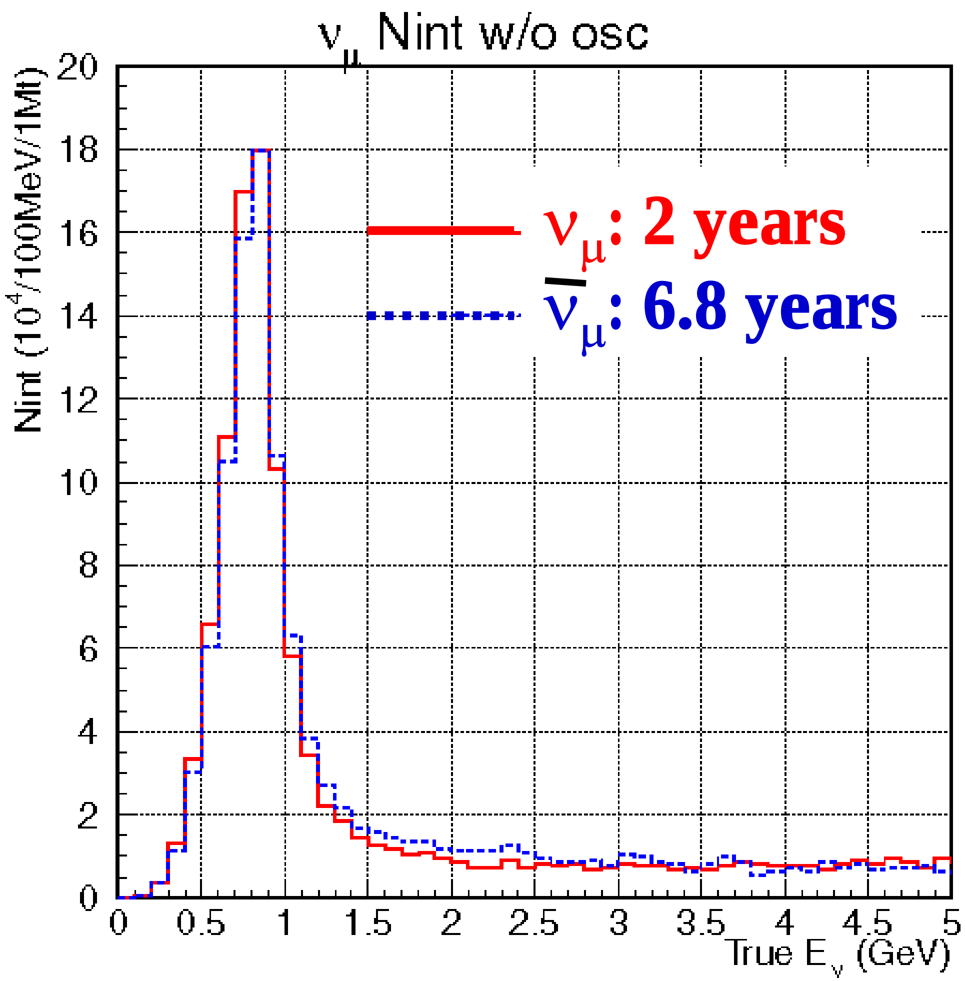
Mass hierarchy



Feldman, Aspen PAC 2004

ν / $\bar{\nu}$ CC interaction spectrum for CPV meas.





Complementarily of Reactor-Accelerator Meas.

Reactor Measurement= Pure $\sin^2 2\theta_{13}$ measurement

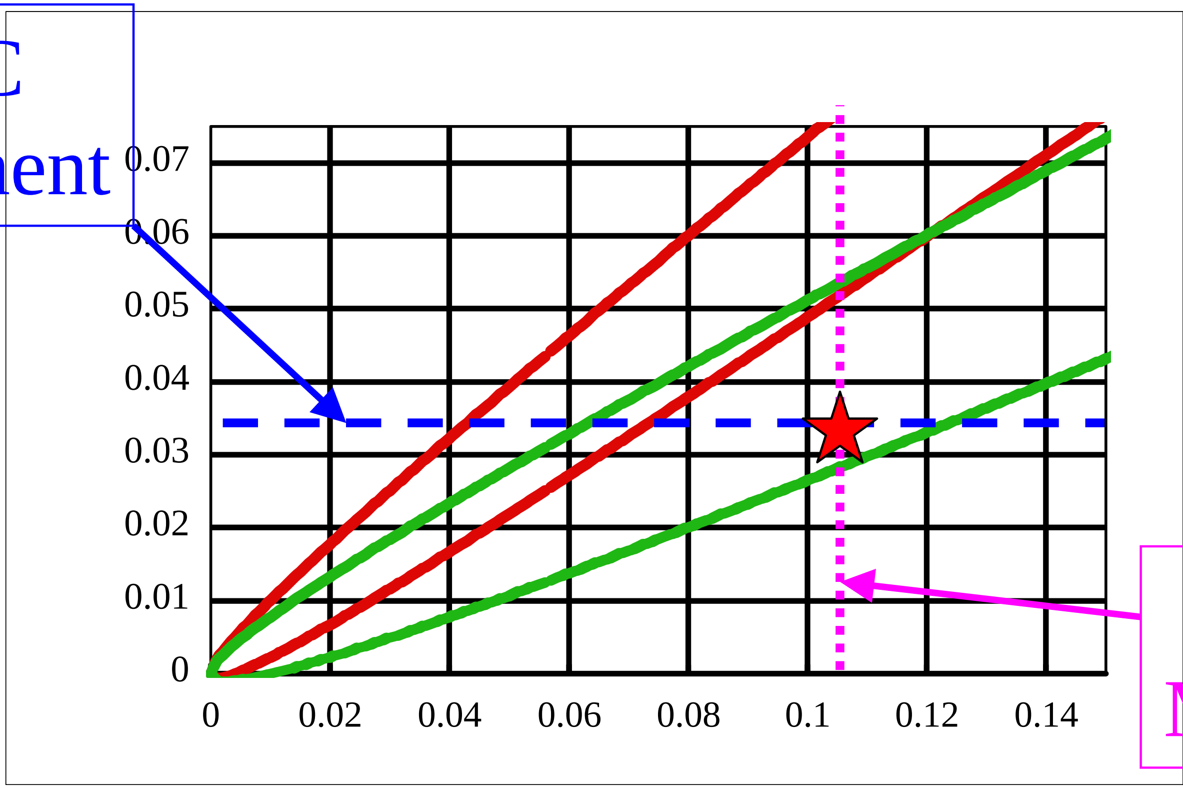
Reactor-Accelerator combination
=> a lot of physics potential

* Answer to θ_{23} degeneracy

$$\sin^2\theta_{23} = \begin{cases} \cancel{0.61} \\ 0.39 \end{cases}$$

J-PARC Measurement

$P(\nu_\mu \to \nu_e)$



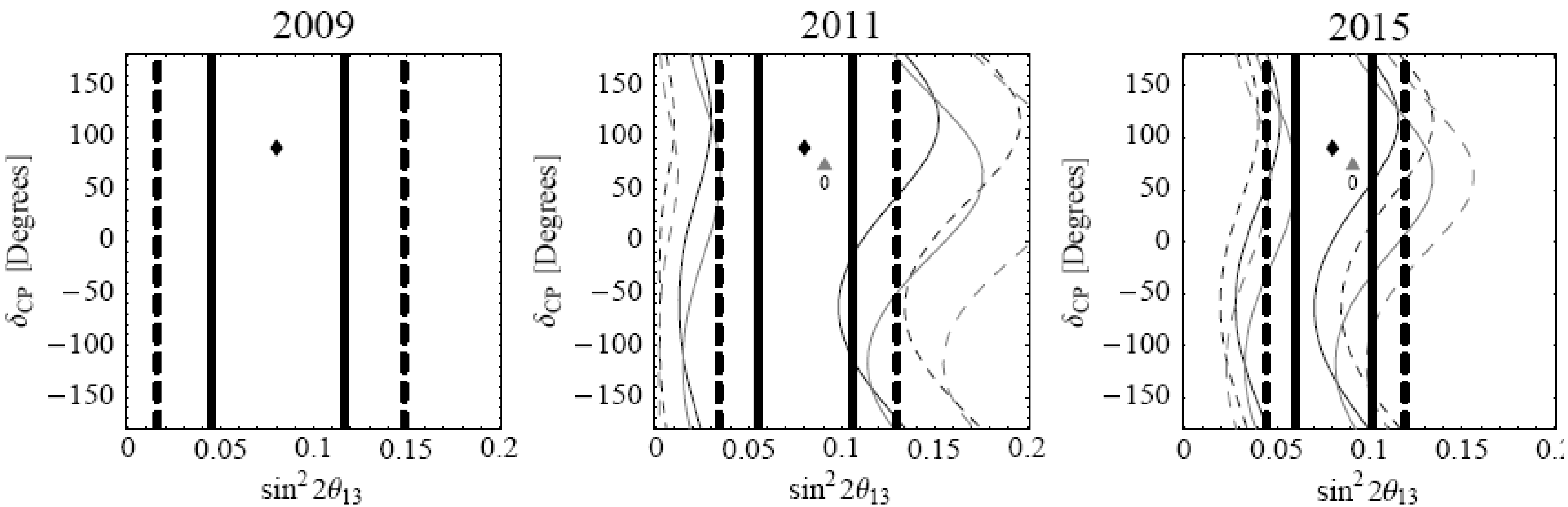
$\sin^2 2\theta_{13}$

* If accuracy is good enough
=> $|\sin\delta_l|$

Reactor Measurement

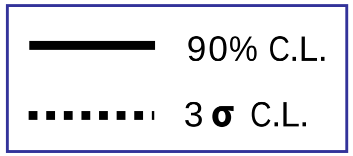
Attempt to compare Double-Chooz with T2K (3 σ discovery potential)

Assumption: Double-CHOOZ starts ***with two detectors*** in January 2008
T2K starts at ***FULL*** intensity in January 2010

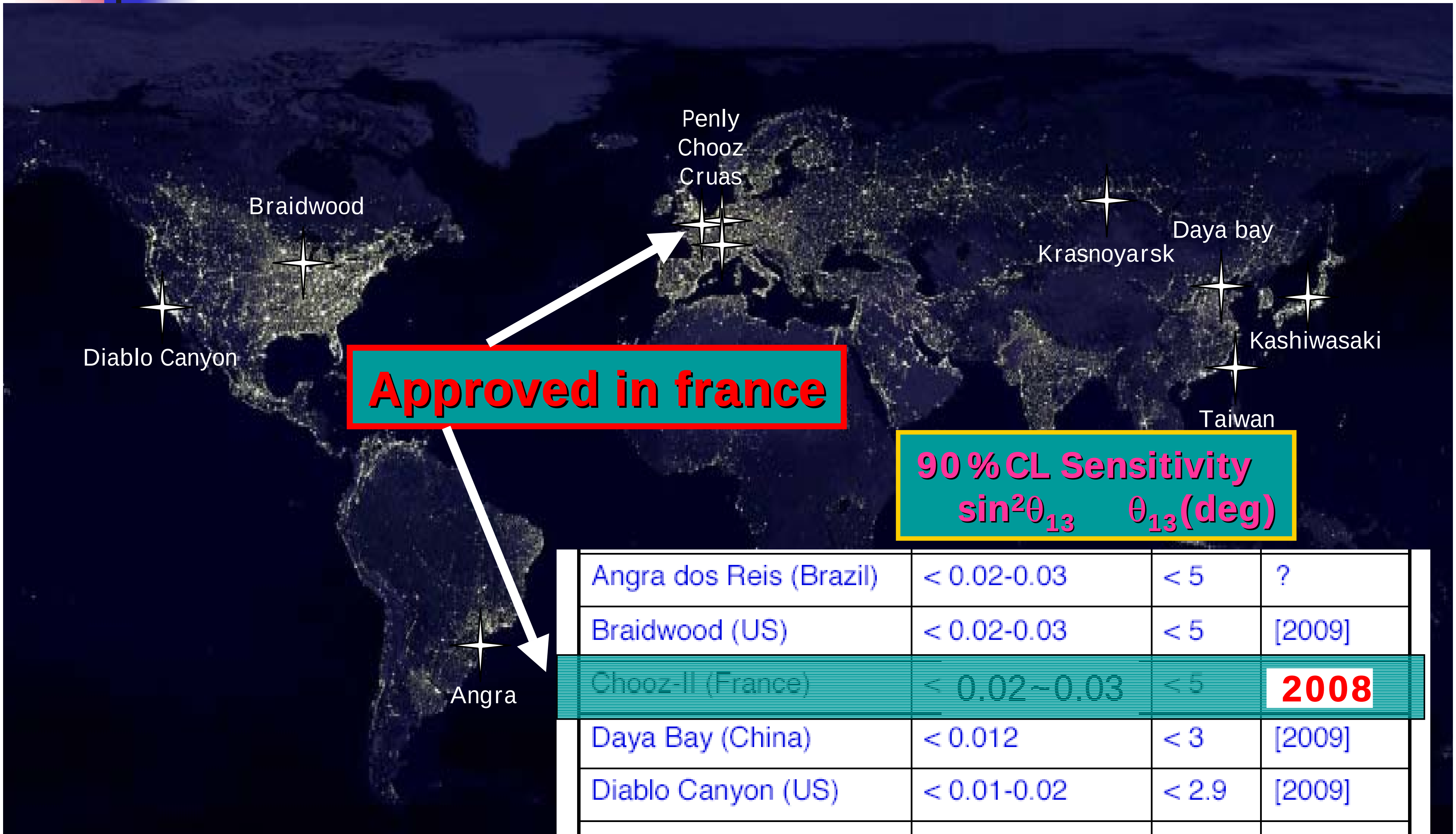


$\sin^2 2\theta_{13} = 0.08$

From Huber, Lindner, Schwetz (hep/0405032)



Reactor experiment proposals

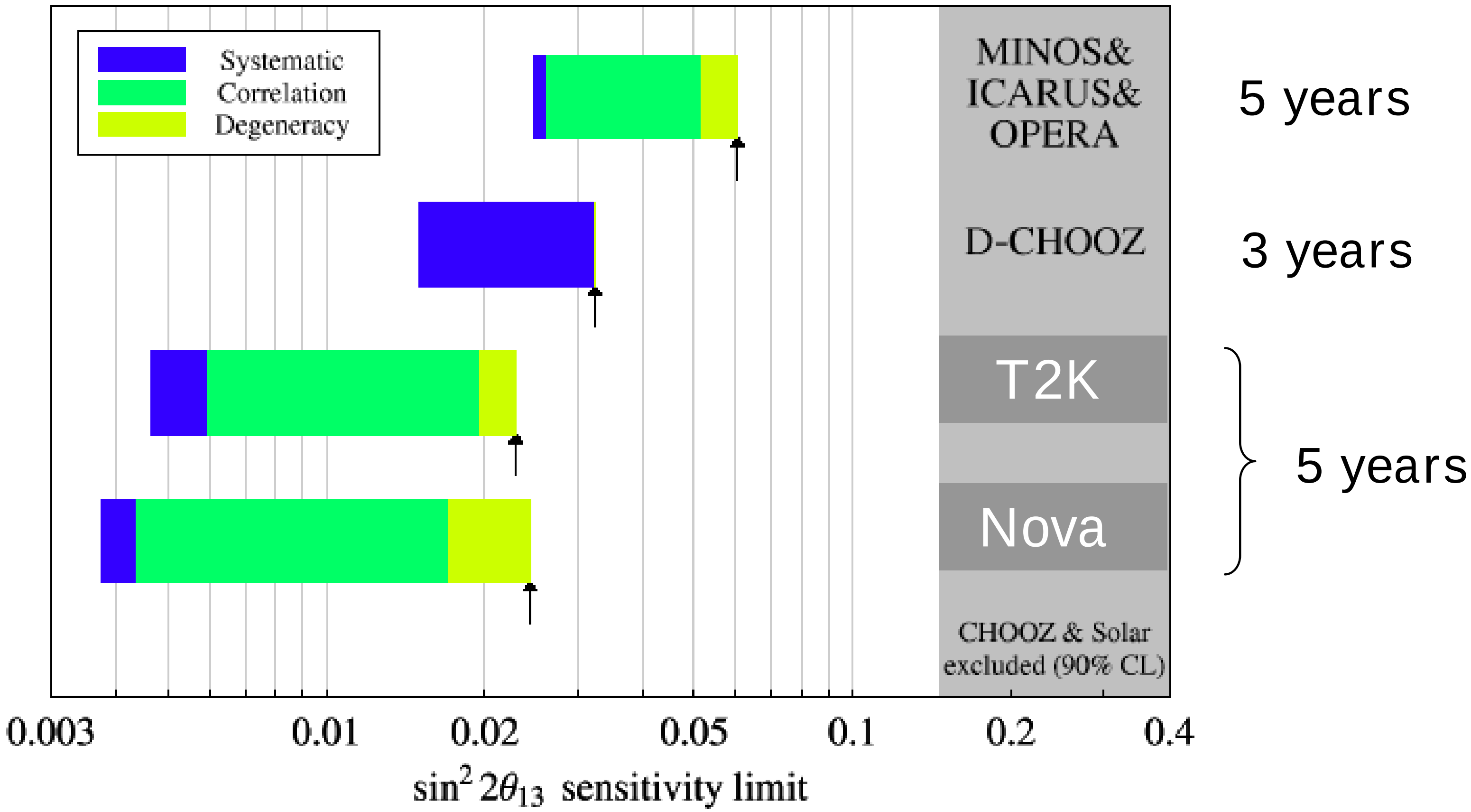


90 % CL Sensitivity

	$\sin^2\theta_{13}$	θ_{13}(deg)	
Angra dos Reis (Brazil)	< 0.02-0.03	< 5	?
Braidwood (US)	< 0.02-0.03	< 5	[2009]
Chooz-II (France)	< 0.02~0.03	< 5	**2008**
Daya Bay (China)	< 0.012	< 3	[2009]
Diablo Canyon (US)	< 0.01-0.02	< 2.9	[2009]
Krasnoyarsk (Russia)	< 0.016	< 3.6	?
Kashiwazaki (Japan)	< 0.026	< 4.6	[2008]

$\sin^2(2\theta_{13})$ at LBL & reactors

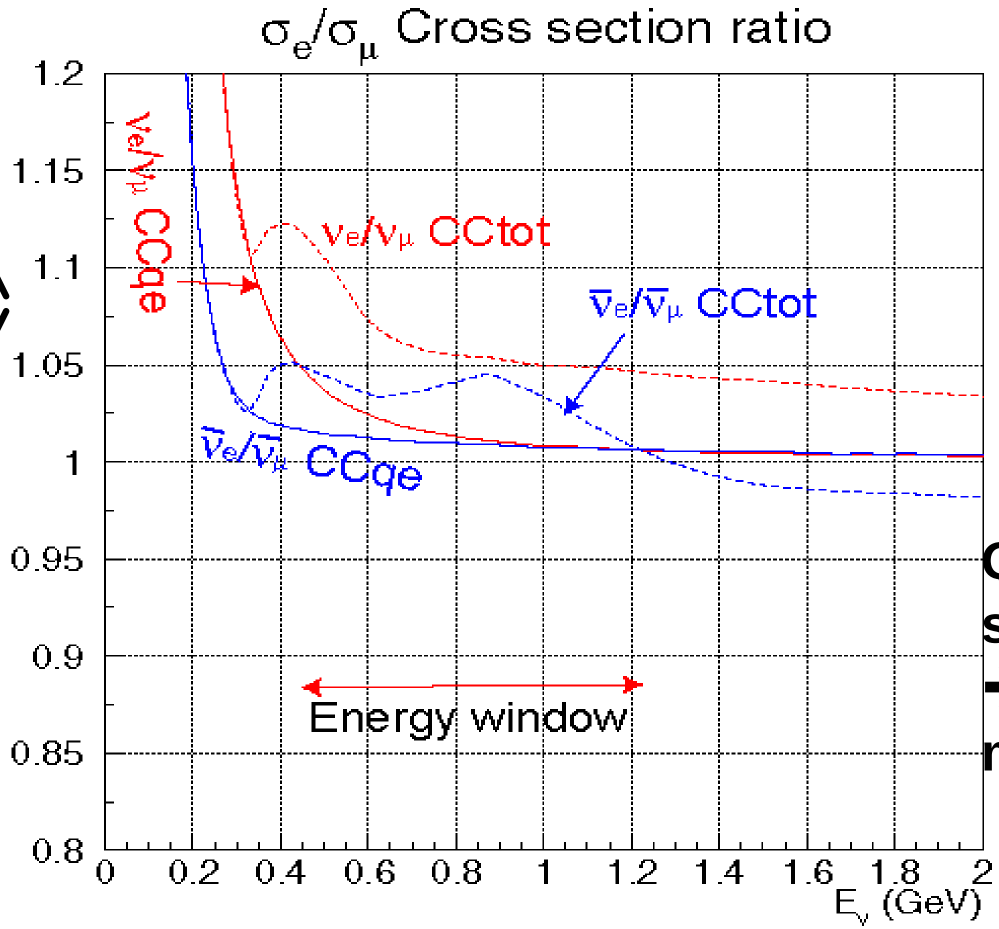
$\Delta m^2 = 2.0\ 10^{-3}\ eV^2$



P. Huber et. al. hep/0403068

Cross section difference

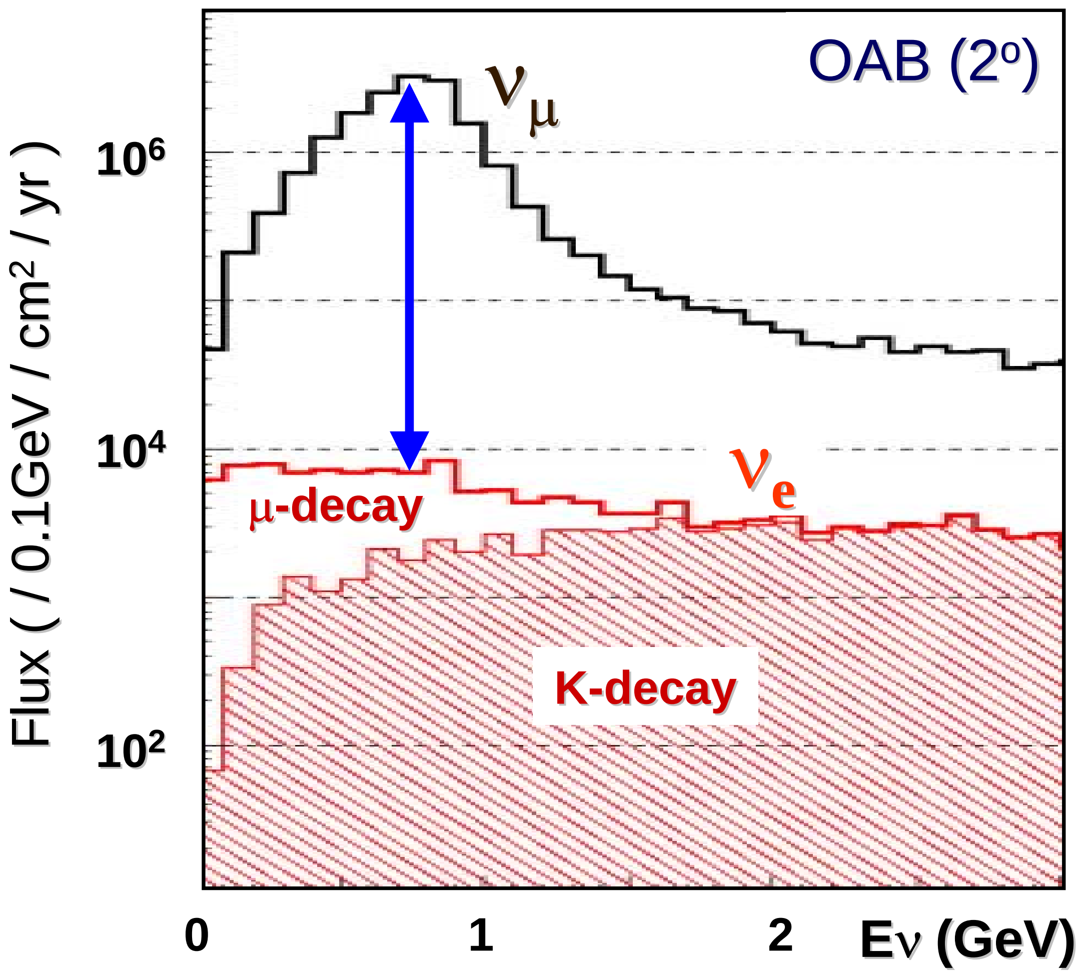
~5% ⇕



CCqe ratio diff
1~5% @ energy window

Quick rise in low energy side → need detailed info.
➔ cross section measurement? (νfact?)

ν_e contamination



- ~ *0.2%* **at ν_μ peak**

Introduction

- K2K : the 1st LBL experiment in operation
  - Powerful probe to investigate neutrino mass/mixing
  - Statistical error dominant
- T2K : the 1st Superbeam LBL Experiment
  - Phase-I : *100×K2K*, JPARC(750kW)→Super-Kamiokande
    - Precision measurements on neutrino mass and mixing
  - Phase-II: *100×Ph.-I*, Super-JPARC(4MW) →Hyper-Kamiokande
    - CPV in lepton sector → Crucial key to study the origin of CPV

Maki-Nakagawa-Sakata (MNS) matrix $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$ $s_{ij}=\sin\theta_{ij},\ c_{ij}=\cos\theta_{ij}$

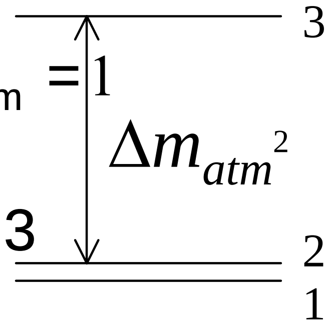
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P_{l\to m} = \left|\langle \nu_m(t) | \nu_l(0)\rangle\right|^2 = \delta_{ml} - 2\sum_{i<j} \mathrm{Re}\left[\left(U_{mi}^* U_{li}\right) \cdot \left(U_{mj} U_{lj}^*\right) \cdot \left\{ 1 - \exp\left(-i \frac{\Delta m_{ij}^2}{2E} L \right) \right\} \right]$$

L : flight length, E : neutrino energy, $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$, m_i : mass eigenvalues

Current Knowledge

- Atm-ν : $\Delta m_{atm}^2 = (1.5 \sim 3.4) \times 10^{-3}\ eV^2$, $\sin^2 2\theta_{atm} > 0.92$
  $\Delta m_{atm}^2 = (1.9 \sim 3.0) \times 10^{-3}\ eV^2$, $\sin^2 2\theta_{atm} > 0.90$ (SK L/E)
  K2K : $\Delta m_{atm}^2 = (1.7 \sim 3.5) \times 10^{-3}\ eV^2$ @ $\sin^2 2\theta_{atm} = 1$
- Solar ν + KamLAND:
  $\Delta m_{sol}^2 = 7.7 \sim 8.8 \times 10^{-5}\ eV^2$, $\tan^2\theta_{sol} = 0.33 \sim 0.49$



Oscillation probabilities in T2K-relevant L/E

$$\begin{cases} \Delta m_{12}^2 \equiv \Delta m_{sol}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2 \equiv \Delta m_{atm}^2 \\ E_\nu \approx \Delta m_{atm}^2 \cdot L \end{cases}$$

small contribution from Δm_{12}

$$\Phi_{23} \equiv 1.27 \Delta m_{atm}^2 L / E_\nu$$

$$P_{\mu \to x} = 1 - (P_{\mu \to e} + P_{\mu \to \tau} + P_{\mu \to sterile}) \approx P_{\mu \to \tau}$$

- ν_μ disappearance

$$P_{\mu \to \tau} \approx \underbrace{\cos^4 \theta_{13}}_{\sim 1} \cdot \sin^2 2\theta_{23} \cdot \sin^2 \Phi_{23} \equiv \sin^2 2\theta_{\mu\tau} \cdot \sin^2 \Phi_{23}$$

- ν_e appearance

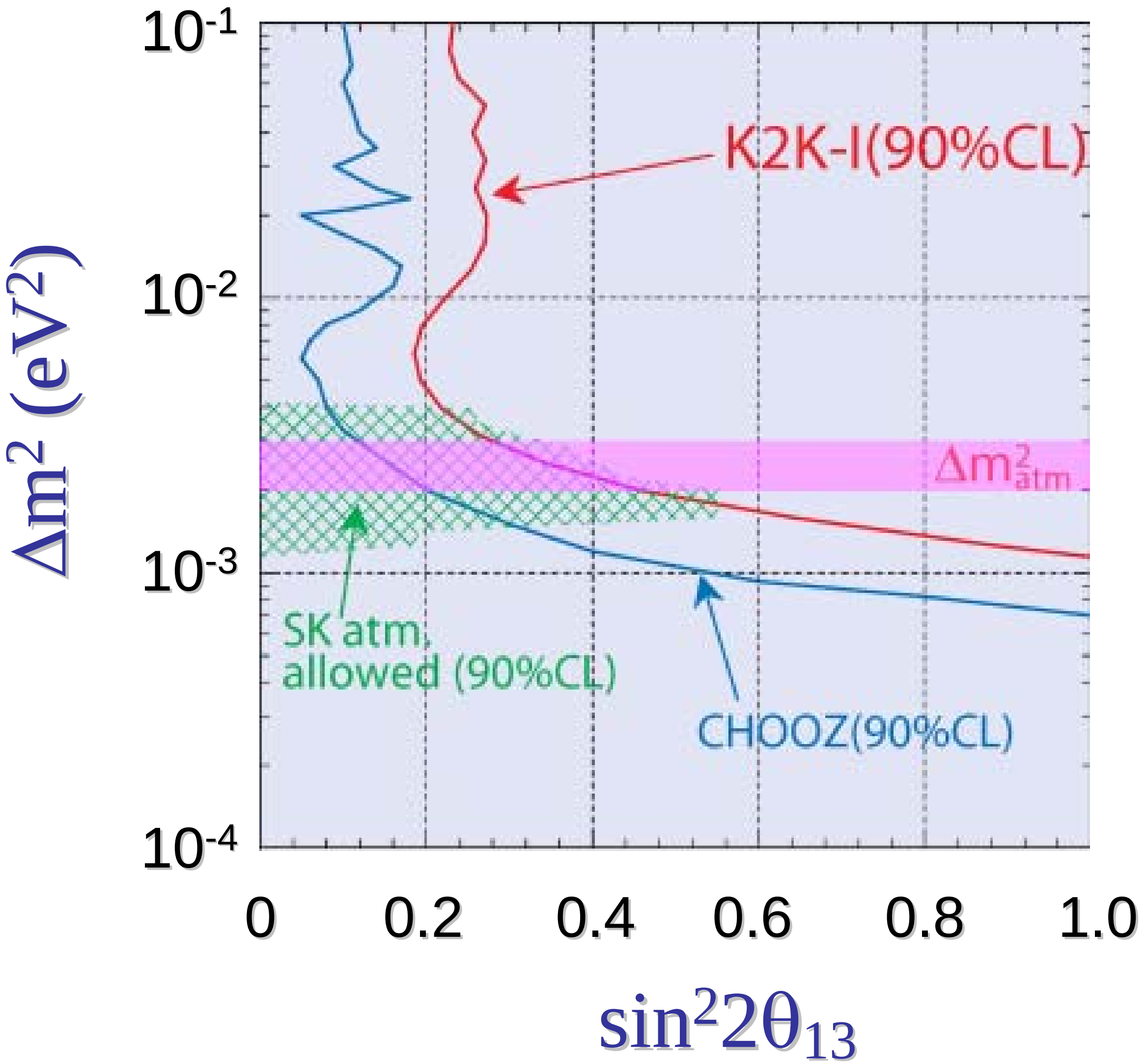
$$P_{\mu \to e} \approx \underbrace{\sin^2 \theta_{23}}_{\sim 1/2} \cdot \sin^2 2\theta_{13} \cdot \sin^2 \Phi_{23} \equiv \sin^2 2\theta_{\mu e} \cdot \sin^2 \Phi_{23}$$

- ν_e disappearance

$$P_{e \to x} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2 \Phi_{23}$$

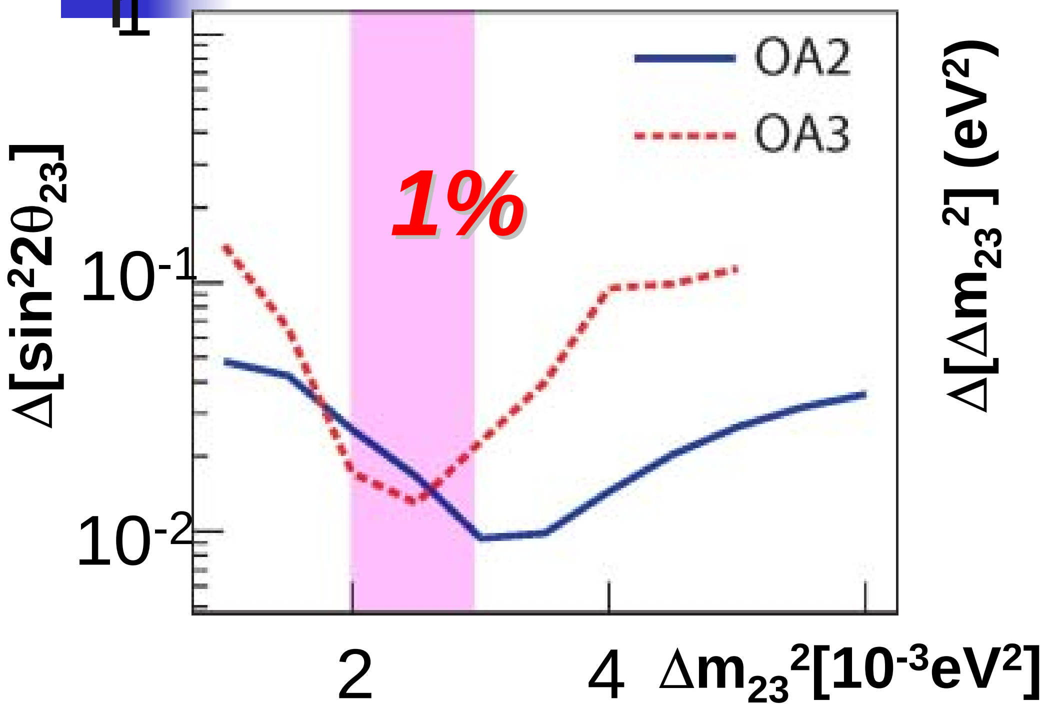
- CHOOZ(1km/3MeV) = $\sin^2 2\theta_{13} < 0.12 \sim 0.20$ @ Δm_{atm}^2

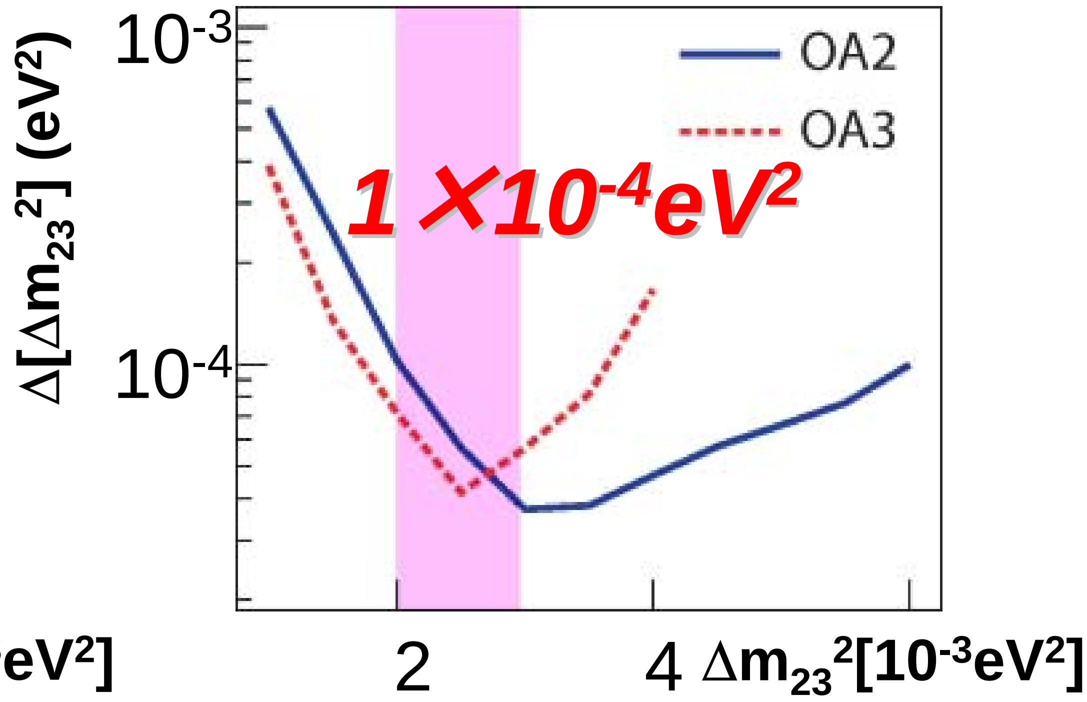
θ_{13} : the Last Unknown Mixing Angle



(Overlay by assuming $\sin^2\theta_{23} = ½$)

Sensitivity for $\sin^2 2\theta_{23}$, Δm_{23}^2





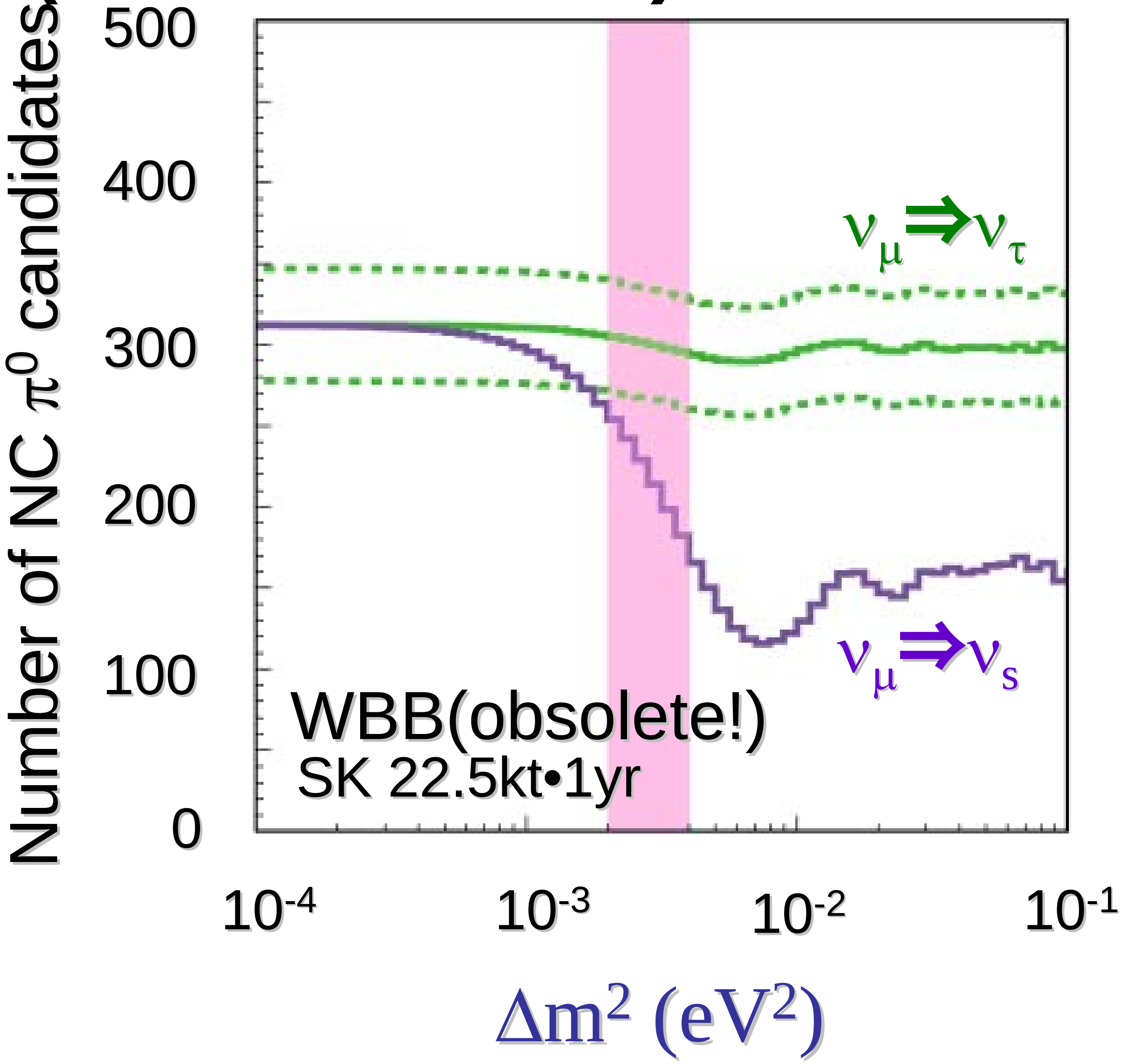
Assumed Systematic Errors

Far-near ratio	10%
non-QE/QE ratio	20%
Energy scale	4%

- Errors will be further improved by 280m measurements, pion production measurements, and 2km measurements !

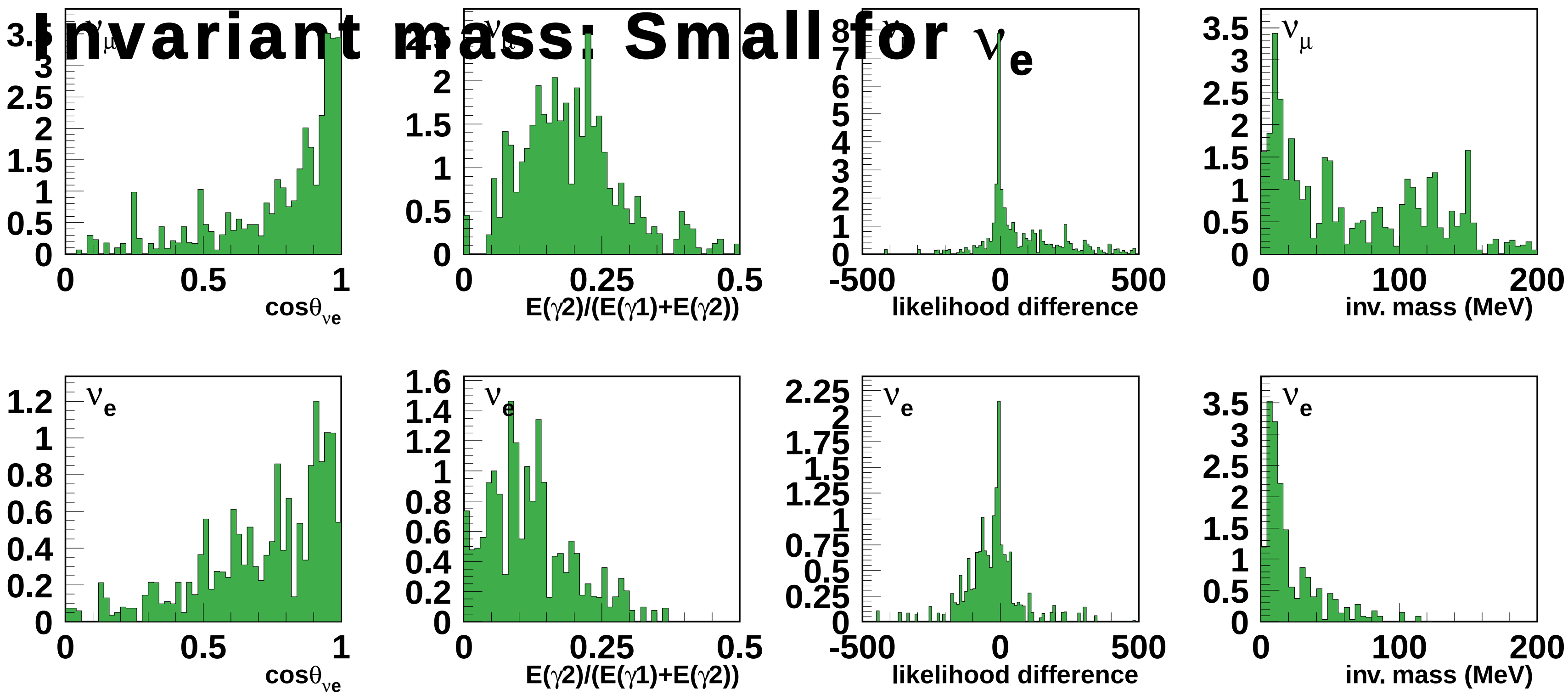
Search for sterile neutrinos

- **Select NC π^0 events**
- **For OA2 5yr, 280⇔680 ($\Delta m^2 = 3\times10^{-3} eV^2$)**



Tight e/π^0 separation

- $\cos\theta_{\nu e}$: γ from π^0 tend to have a forward peak
- $E(\gamma_2)/E(\gamma_1+\gamma_2)$: Large for BG
- Likelihood diff. between 1-ring and 2-rings
- Invariant mass: Small for ν_e



T2K sensitivity to ν_e appearance

Contents:

1. Effect of the degeneracy in θ_{23}
2. Contributions from θ_{12}

   with exact oscillation formula
3. Sensitivity as a function of CP phase δ
4. Comment on resolving normal/inverted mass hierarchy

Configuration

- Beam MC: Flux04a
  - 40 GeV primary proton beam
  - 130 m long decay pipe
  - 2.5 deg. off-axis beam
- 5 years (10^{21} POT/year)
- SK fiducial volume: 22.5 kt
- Event selection:
  - FCFV 1-ring e-like with no decay electron
  - Further cuts for π^0 rejection
    - Ref. NP04 Mine-san's presentation: http://jnusrv01.kek.jp/jhfnu/NP04nu/PresenFiles/sk/
- Uncertainty in B.G. estimation = 10%

Assumption for the studies

- Δm^2_{12}, θ_{12} : KamLAND2004 + Solar ν

$$\Delta m^2_{12} = 8.2 \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.40$$

- Δm^2_{23}, θ_{23} : Around atmospheric *L*/*E*

$$\Delta m^2_{23} = (1.9 \sim 3.0) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 0.9 \sim 1$$

- Matter effect (set to be zero in this study)

$$a \equiv 2\sqrt{2} G_F n_e E_\nu = 7.56 \times 10^{-5} [\mathrm{eV}^2] \cdot \frac{\rho}{[\mathrm{g/cm}^3]} \cdot \frac{E_\nu}{[\mathrm{GeV}]}$$

$$(\rho = 2.8\ \mathrm{g/cm}^3)$$

- No CP violation (CP phase δ=0) unless noted

Simplified Oscillation

- ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - 4C_{23}^2 S_{23}^2 C_{13}^4 \cdot \sin^2 \Delta_{32} - P(\nu_\mu \to \nu_e)$$

- ν_e appearance

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

- beam $\nu_e \to \nu_e$ oscillation

$$P(\nu_e \to \nu_e) = 1 - 4C_{13}^2 S_{13}^2 \sin^2 \Delta_{13}$$

assuming $\Delta m_{32}^2 = \Delta m_{31}^2 \ \ (\Delta m_{21}^2 = 0)$

Exact Oscillation

- ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - 4(C_{12}^2 C_{23}^2 + S_{12}^2 S_{13}^2 S_{23}^2 - 2C_{12}C_{23}S_{12}S_{13}S_{23}\cos\delta)S_{23}^2 C_{13}^2 \cdot \sin^2\Delta_{23}$$
$$- 4(S_{12}^2 C_{23}^2 + C_{12}^2 S_{13}^2 S_{23}^2 + 2C_{12}C_{23}S_{12}S_{13}S_{23}\cos\delta)S_{23}^2 C_{13}^2 \cdot \sin^2\Delta_{13}$$
$$- 4(C_{12}^2 C_{23}^2 + S_{12}^2 S_{13}^2 S_{23}^2 - 2C_{12}C_{23}S_{12}S_{13}S_{23}\cos\delta)$$
$$\times (C_{12}^2 C_{23}^2 + S_{12}^2 S_{13}^2 S_{23}^2 + 2C_{12}C_{23}S_{12}S_{13}S_{23}\cos\delta) \cdot \sin^2\Delta_{12}$$

- ν_e appearance

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \left(1 + \frac{2a}{\Delta m_{13}^2}(1 - 2S_{13}^2)\right) \cdot \sin^2\Delta_{31}$$
$$+ 8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$
$$- 8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$
$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2\Delta_{21}$$
$$- 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

- beam $\nu_e \to \nu_e$ oscillation

$$P(\nu_e \to \nu_e) = 1 - 4C_{13}^2 S_{13}^2 \cdot \left(C_{12}^2 \sin^2\Delta_{13} + S_{12}^2 \sin^2\Delta_{23}\right) - 4S_{12}^2 C_{12}^2 C_{13}^4 \sin^2\Delta_{12}$$

$$\Delta m_{31}^2 = \Delta m_{21}^2 + \Delta m_{32}^2$$

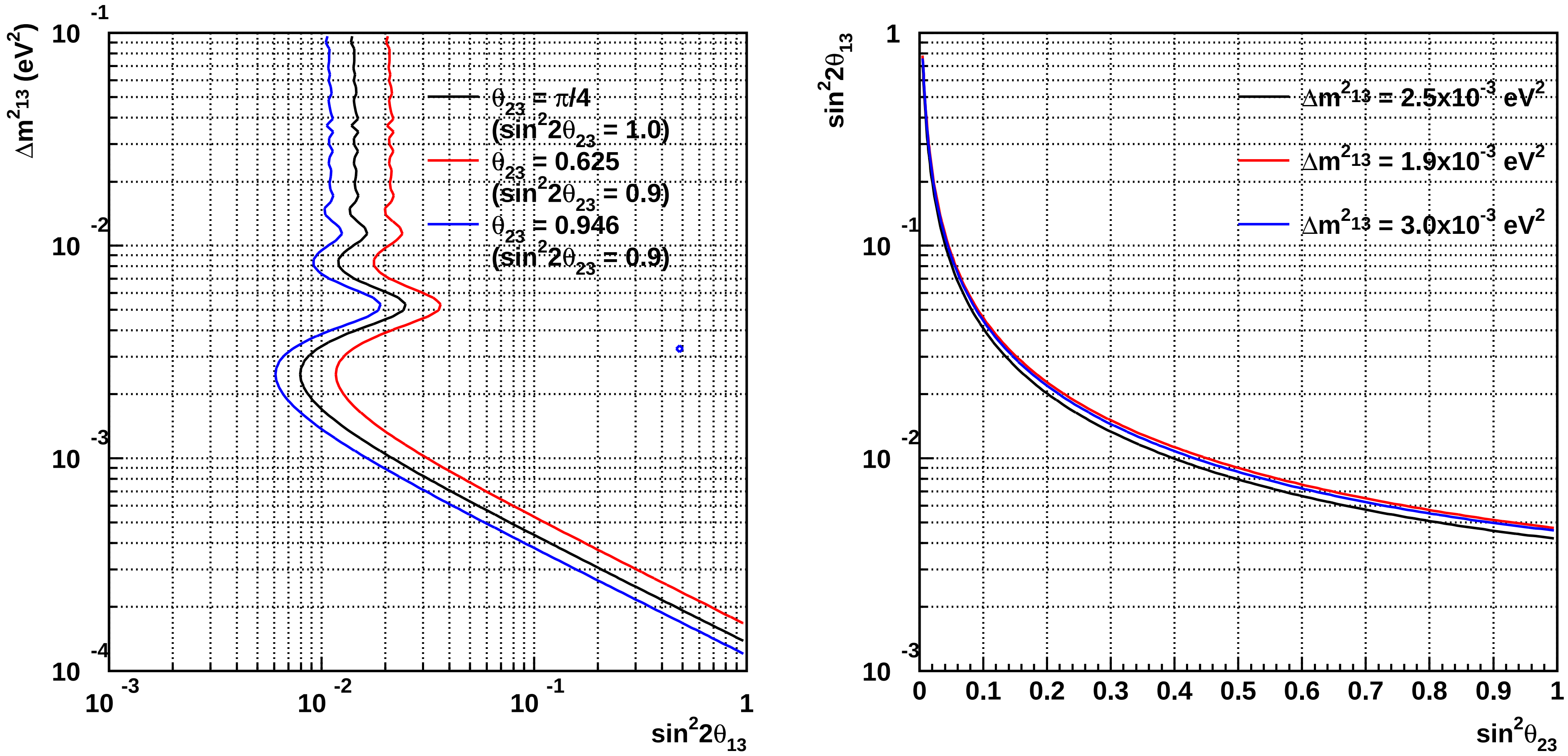
with a relation of

Changes from Mine-san's version

Mine-san's version:
http://jnusrv01.kek.jp/~jnurep/physics/nue/mine_nue_sk40gev.ppt

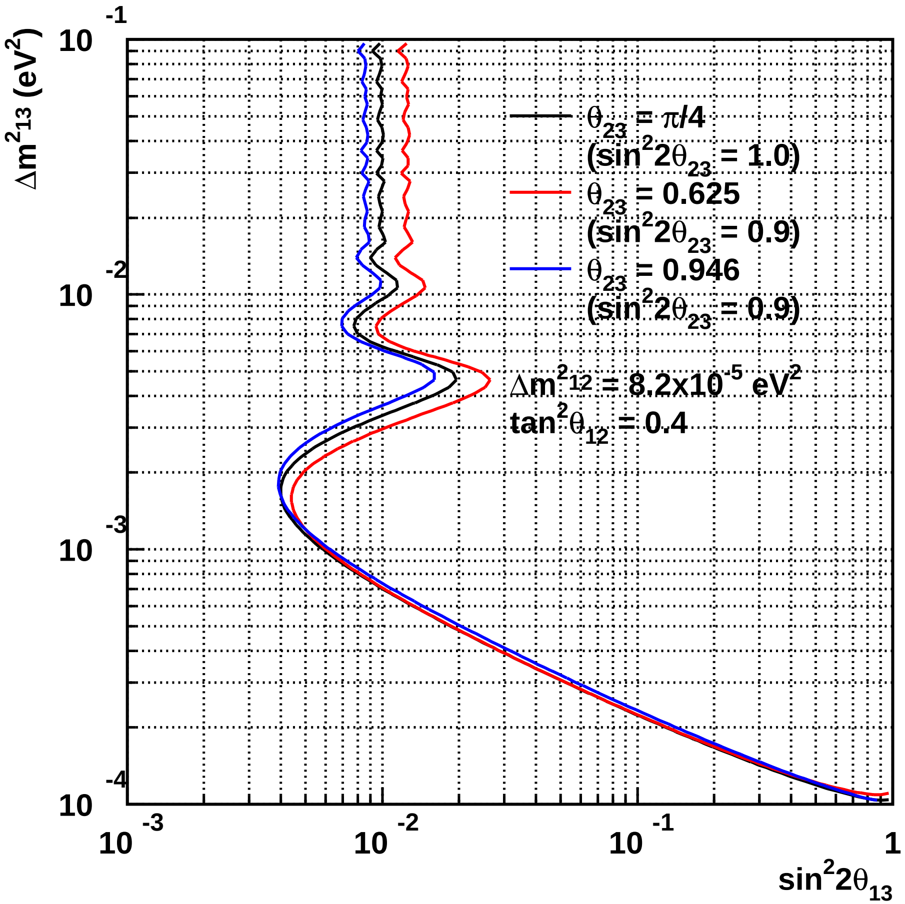
- Two small bugs are fixed
  - Use 'amome' instead of 'amom' in $E\nu_e$ reconstruction
    - Impact:: oscillated ν_e(CC) signal: 103 → 105 events
      at $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{13}=2.5\text{x}10^{-3}$ eV^2
  - Oscillation formula for beam $\nu_e \rightarrow \nu_e$ oscillation in "simple version"
    $(1/2)*\sin^2 2\theta_{13}*\sin^2\Delta_{13} \rightarrow \sin^2 2\theta_{13}*\sin^2\Delta_{13}$
    - Impact:: beam ν_e B.G.: 13 → 14 events
      at $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{13}=2.5\text{x}10^{-3}$ eV^2
- Change in $\nu_\mu \rightarrow \nu_\mu$ oscillation formula in "simple version"
  - $1 - \sin^2 2\theta_{23}*\sin^2\Delta_{23} \rightarrow 1 - \sin^2 2\theta_{23}*\cos^4\theta_{13}*\sin^2\Delta_{23} - P(\nu_\mu \rightarrow \nu_e)$
    - Impact:: negligible effect at $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{13}=2.5\text{x}10^{-3}$ eV^2
- Exact formulae for oscillations are included

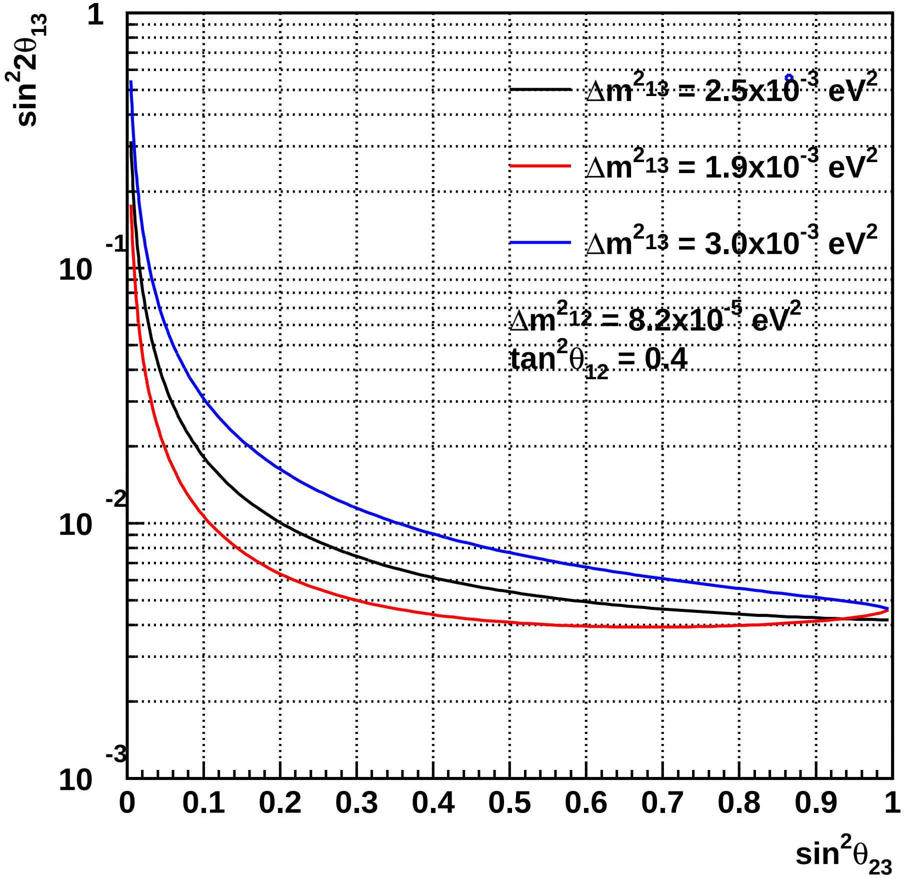
Sensitivity to ν_e appearance (simple oscillation)



- Condition is almost same as Mine-san's version except for a few minor changes (see page 6)

Sensitivity to ν_e appearance (exact oscillation)





- Contribution of θ_{12} terms to ν_e appearance
  - 2.6±0.6 appearance events are expected with "KamLAND2004+Solar" parameters, even if θ_{13} is set to be 0.

Why does the Δm^2 value of the maximum sensitivity to $\sin^2 2\theta$ change between simple and exact versions?

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

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

$$\cancel{-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}}$$

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

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

Matter effect = 0

CP-phase δ = 0

When $\sin^2 2\theta_{13} \sim 0.01$, $\theta_{23} = \pi/4$, $\tan^2\theta_{12} = 0.4$, $\Delta m^2_{12} = 8.2\times10^{-5}$ eV^2, and $E_\nu \sim 0.6$ GeV

1 usual ν_e appearance term: $\sim 0.005 \times \sin^2 \Delta_{13}$

2 $8C_{13}^2 S_{12} S_{13} S_{23} C_{12} C_{23} - 8C_{13}^2 S_{12}^2 S_{13}^2 S_{23}^2 \sim 0.093$

~0.0902 ~0.0029

$$\cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \cong \frac{\Delta_{12}}{2} \sin\Delta_{13} \cdot \cos\Delta_{13} + \boxed{\frac{1}{2}\sin^2\Delta_{12}}$$

~0.026

to be included in 3 but negligible

3 $(4S_{12}^2 C_{13}^2 C_{12}^2 C_{23}^2 + 4C_{13}^2 S_{12}^4 S_{23}^2 S_{13}^2 - 8C_{12} C_{23} C_{13}^2 S_{12}^3 S_{23} S_{13}) \cdot \sin^2\Delta_{21}$

~0.407 ~0.000401 ~0.026 ~0.0026

$$0.005\sin^2\Delta_{13} + 0.0024\sin\Delta_{13}\cos\Delta_{13} + \cancel{0.428\sin^2\Delta_{12}}$$

ignored

$$\approx 0.0055\sin\Delta_{13}\sin(\Delta_{13} + 25.6^\circ)$$

$$= 0.00275[\cos 25.6^\circ - \cos(2\Delta_{13} + 25.6^\circ)] \quad \text{(B)}$$

$$\Leftrightarrow 0.005\sin^2\Delta_{13} = 0.0025(1-\cos 2\Delta_{13}) \quad \text{(A)}$$ (usual case)

A and B are to be compared

(A) has max. at $\Delta_{13} = \pi/2$
→ $\Delta m^2_{13} \sim 2.5 \times 10^{-3}$ eV^2

(B) has max. at $\Delta_{13} = \pi/2 - 0.45$
→ $\Delta m^2_{13} \sim (2.5 - 0.7) \times 10^{-3}$ eV^2

Oscillation probability as a function of E_ν
– contribution from each term –

Plots to see the effect described on previous page

1st term: ① on page 9

2nd term: ②

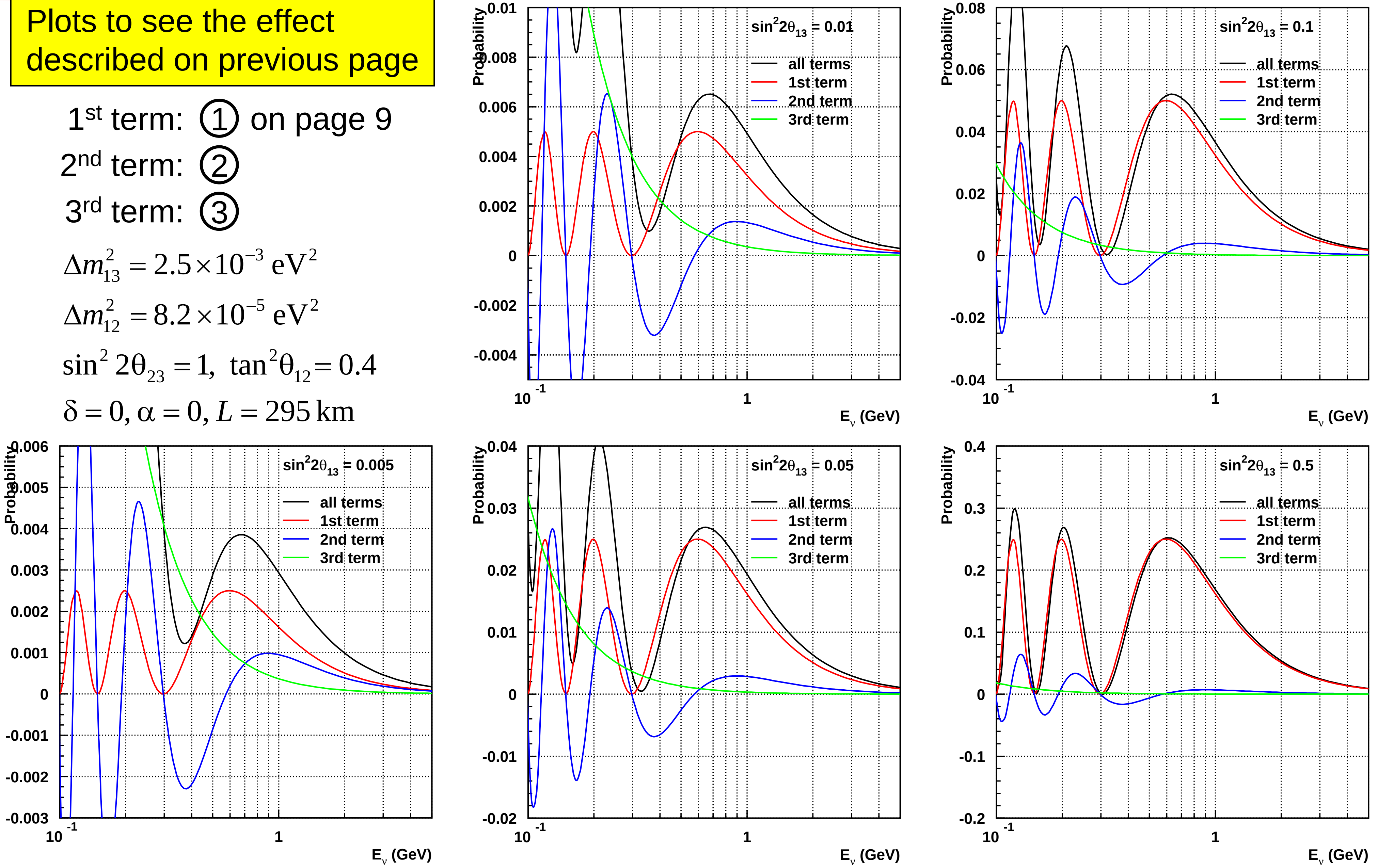
3rd term: ③

$$\Delta m_{13}^2 = 2.5\times10^{-3}\ \mathrm{eV}^2$$

$$\Delta m_{12}^2 = 8.2\times10^{-5}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1,\ \tan^2\theta_{12} = 0.4$$

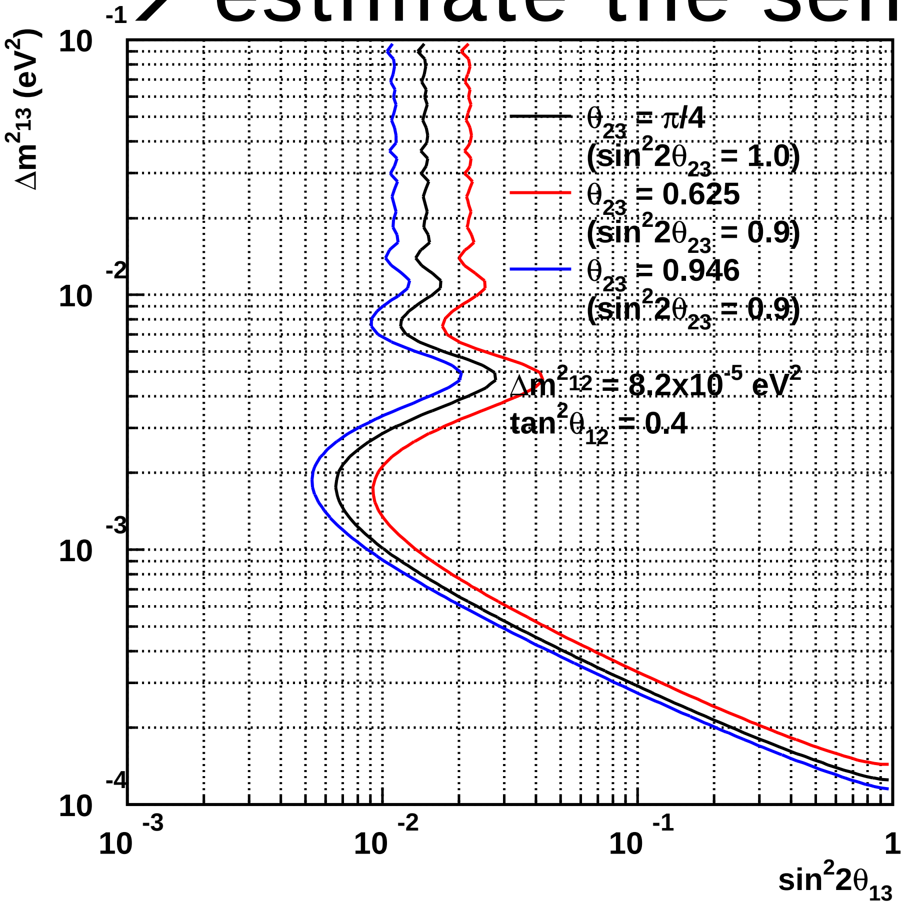
$$\delta = 0, \alpha = 0, L = 295\ \mathrm{km}$$

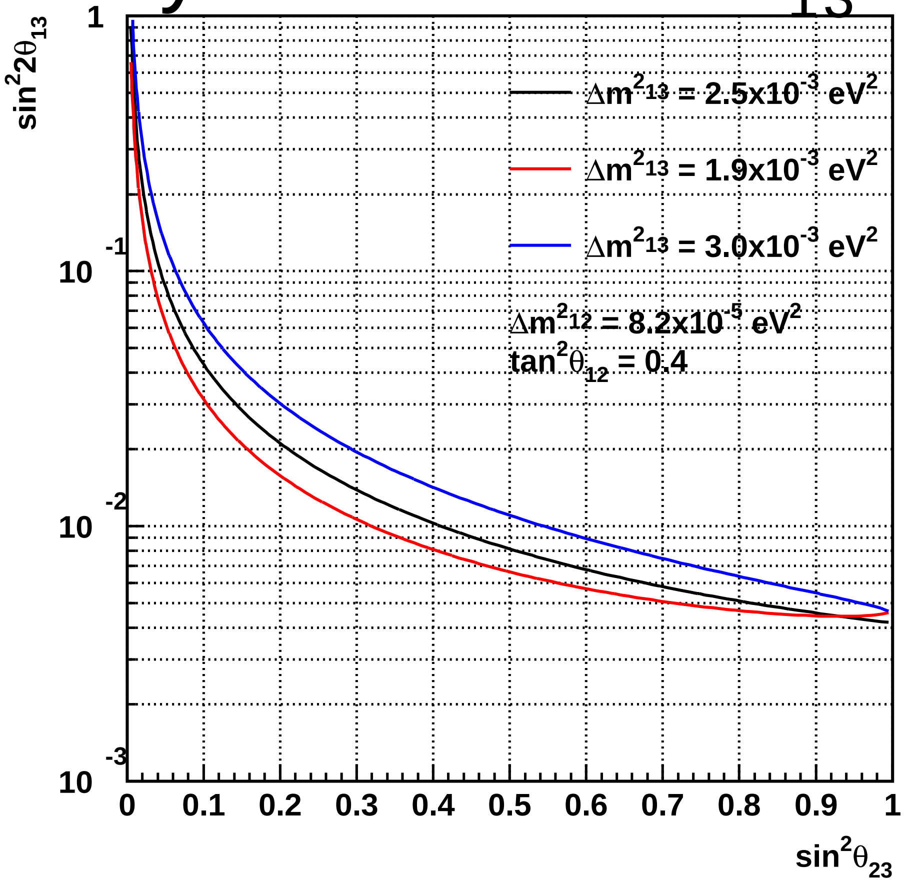


Sensitivity with θ_{12} contribution subtracted

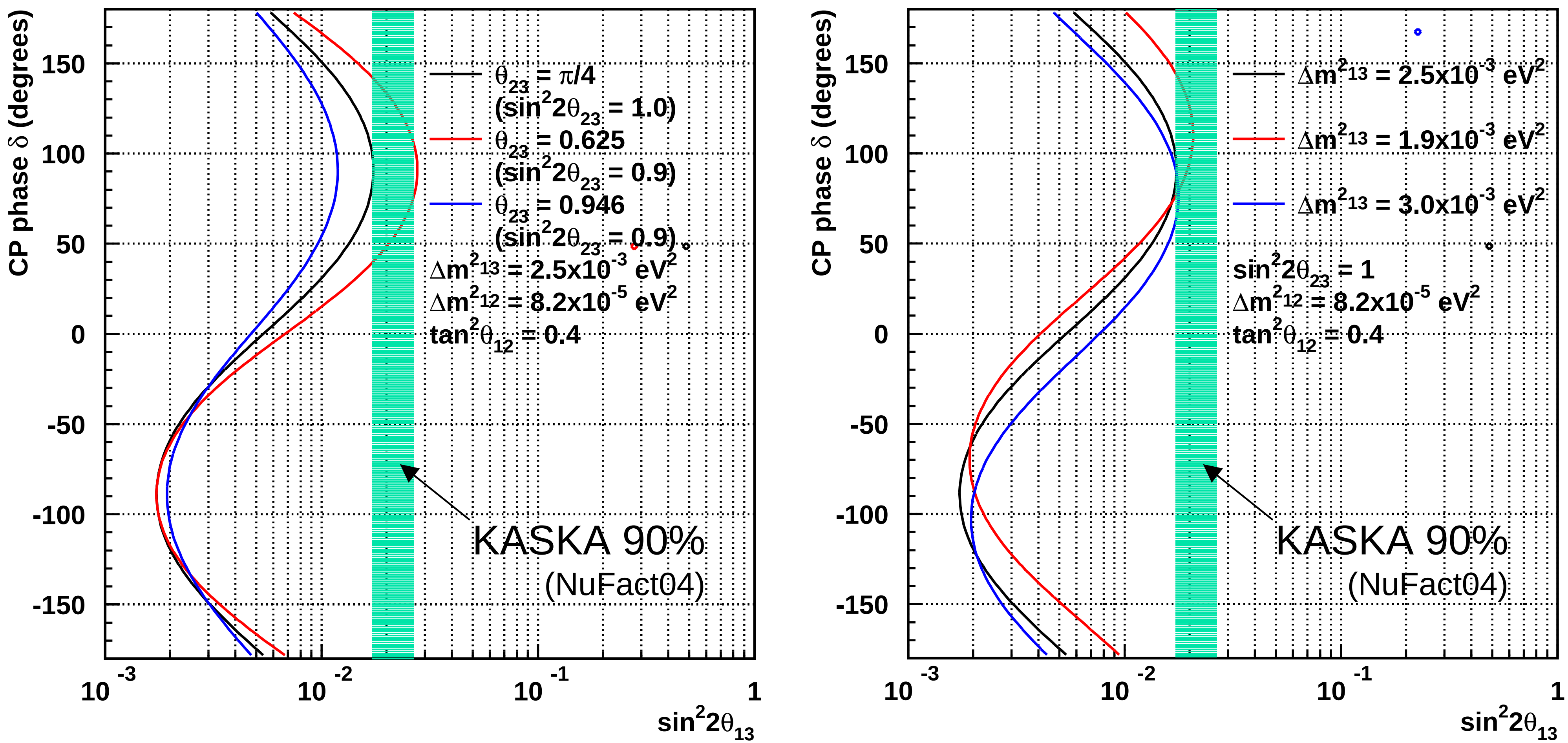
- Contribution of θ_{12} terms (2.6±0.6 events) are simply subtracted from ν_e appearance signals

→ estimate the sensitivity to non-zero θ_{13}

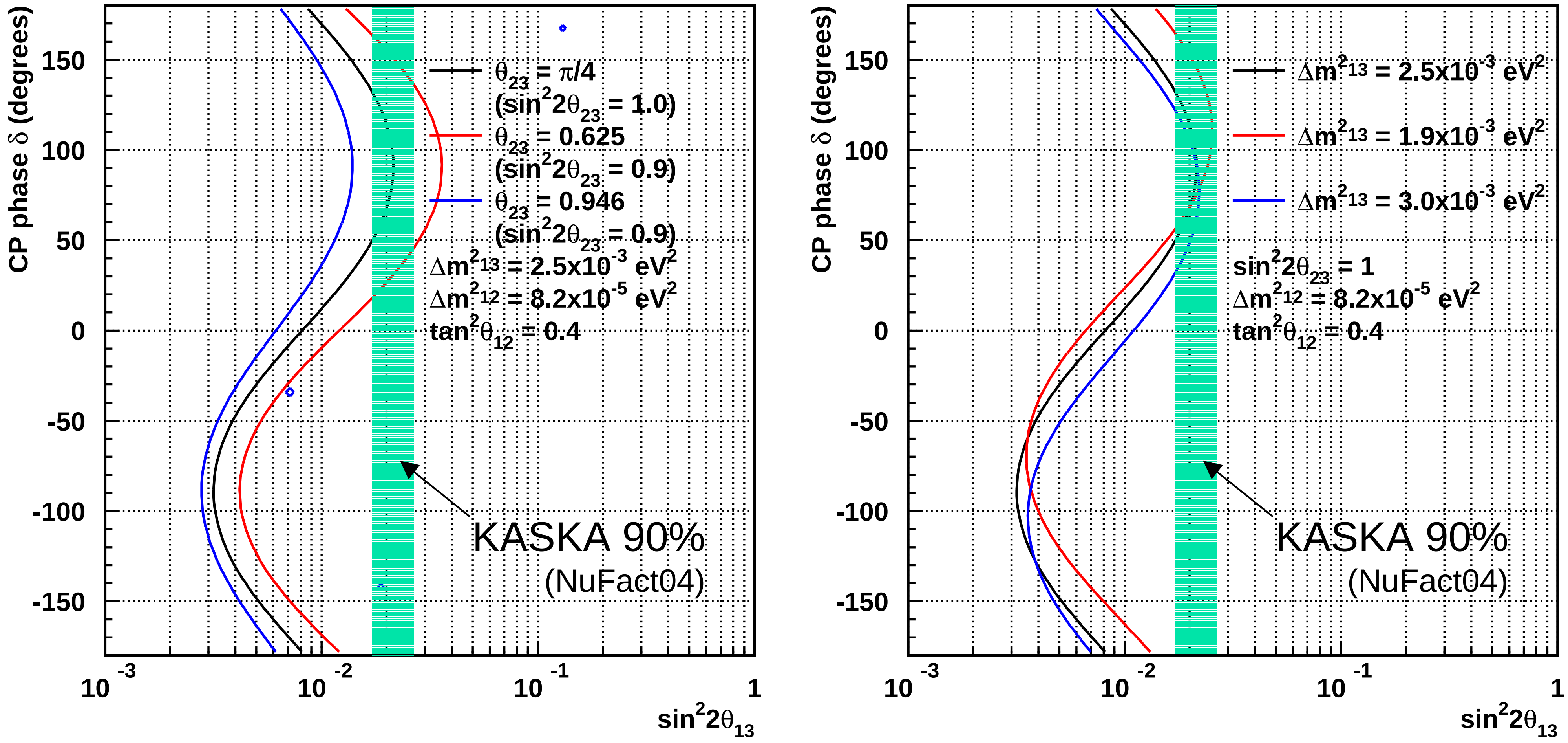




Sensitivity to θ_{13} as a fuction of CP-phase δ (θ_{12} contribution not subtracted)



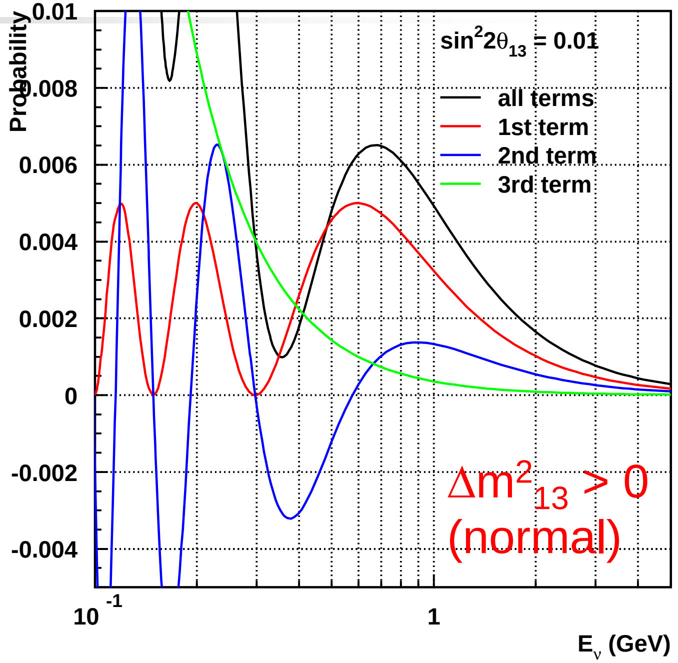
Sensitivity to θ_{13} as a fuction of CP-phase δ (θ_{12} contribution subtracted)

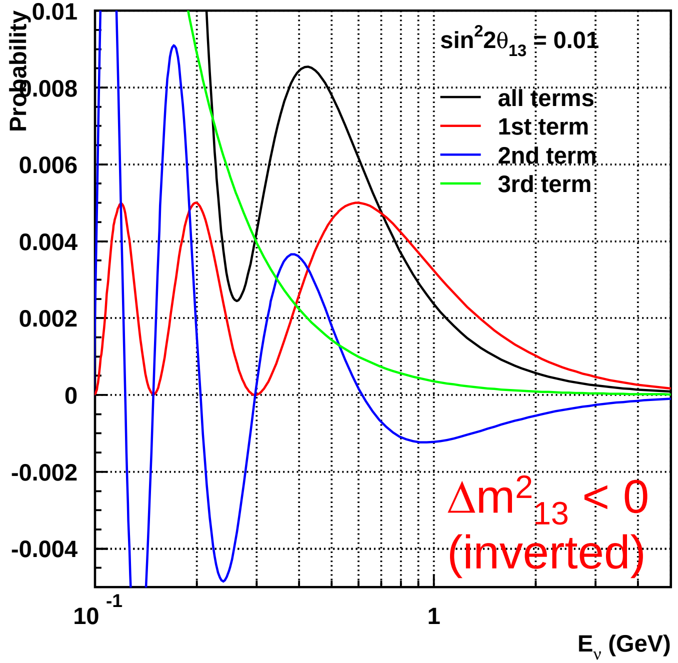


Comment on the sign of Δm^2_{13}

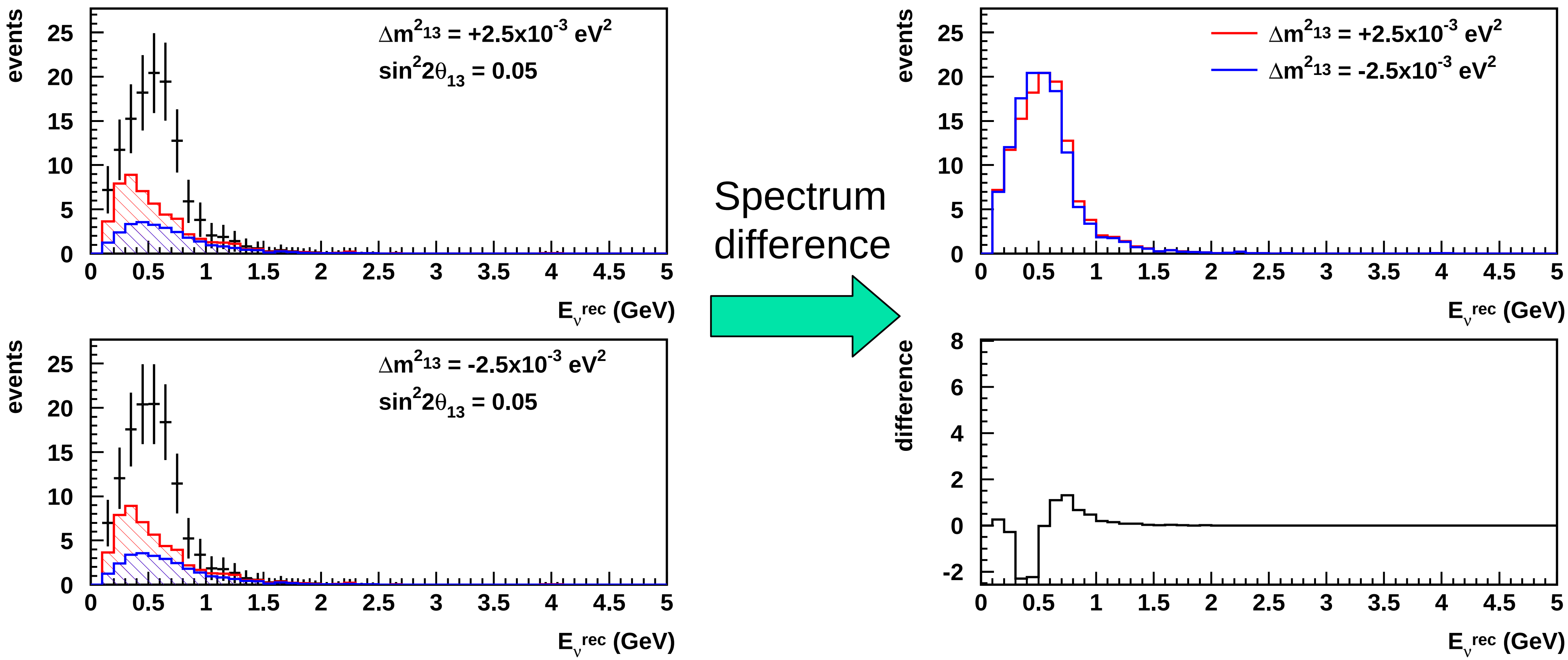
- So far, VLBL experiment is considered to have a capability of probing the sign of Δm^2_{13} via matter effect.
- But, the sign of phase shift described on page 9 alternates according to the sign of Δm^2_{13} and sign of $\cos\delta$.
  (see right figures)
- In T2K,
  - Δm^2_{23} is precisely measured by ν_μ disappearance
  - using this Δm^2_{23}, we can estimate the size of θ_{13} if ν_e appearance is observed.
  - If $\sin^2 2\theta_{13} \sim 0.01 - 0.1$, we may probe the sign of Δm^2_{13} using the ν_e spectral information.
    (The contribution of interference term is also reasonably large around $\sin^2 2\theta_{13} \sim 0.01 - 0.1$)

T2K may have a capability of probing the sign of $(\Delta m^2_{13}) \times (\cos\delta)$, depending on the size of CP-phase δ, θ_{12} and Δm^2_{12}





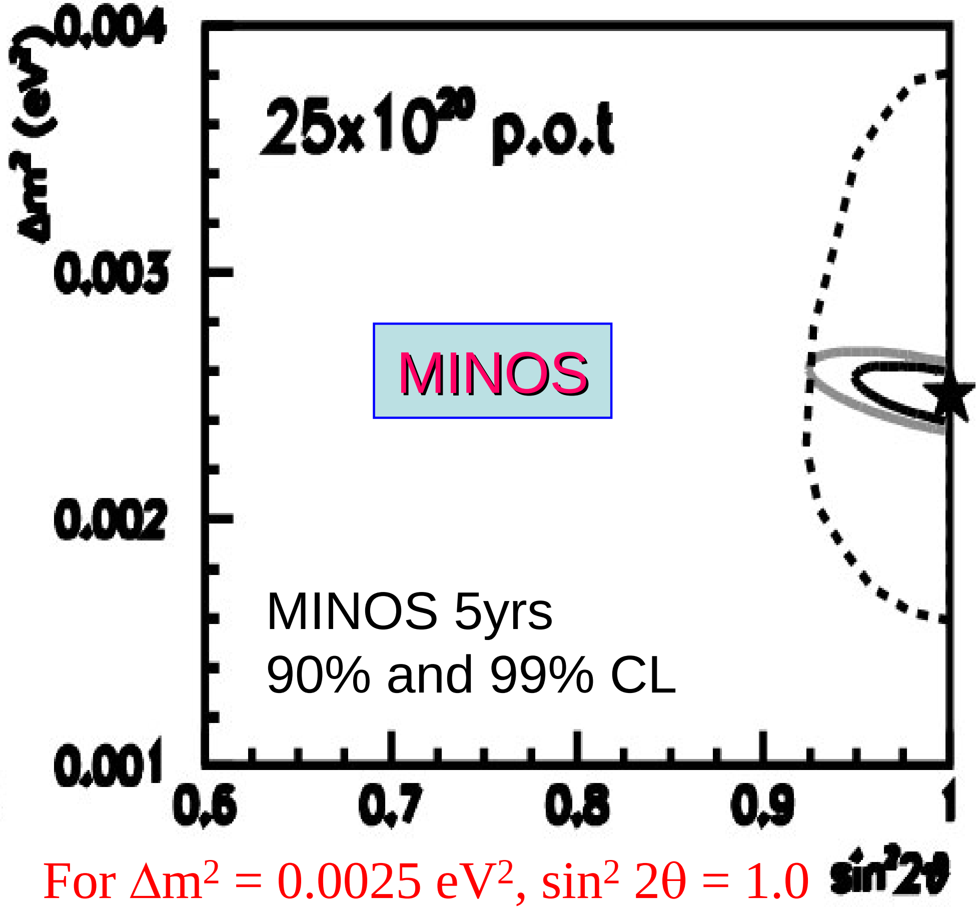
Comment on sign of Δm^2_{13} (cont'd)



- Reconstructed neutrino energy distributions for positive and negative Δm^2_{13}
  - Difference is a bit small to probe…
    → maybe issue of T2K phase-II.

Expected sensitivities

ν_μ disappearance



For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta = 1.0$

$\delta(\Delta m^2) \sim 2x10^{-4} eV^2$

$\delta(\sin^2 2\theta) \sim 5\%$

read from above plot

ν_τ appearance

Expected signal

	Sig	B G
OPERA	17.	1.
ICARUS	2 11.9	1 0.7

$\Delta m^2 = 2.5x10^{-3} eV^2$

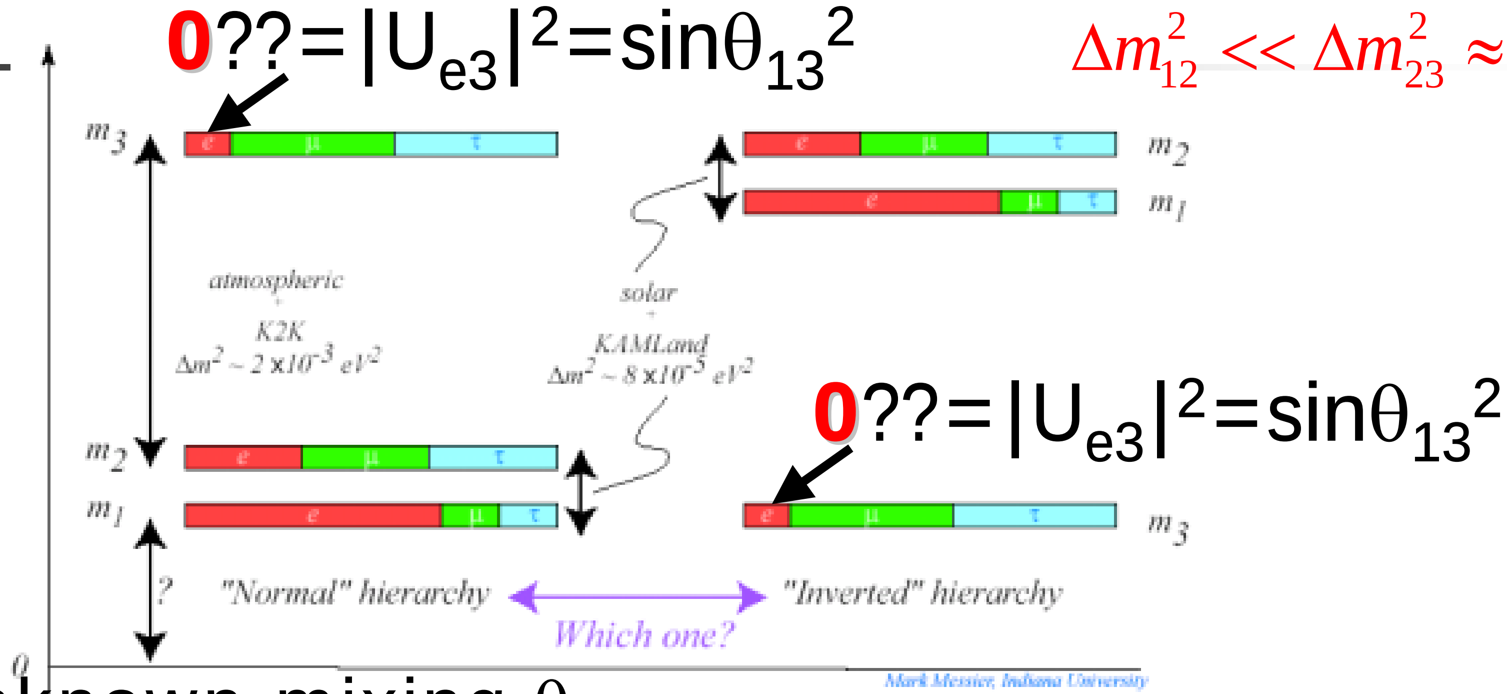
Full mix.

5yrs of running

ICARUS: 1.5kt fid mass

What's next?

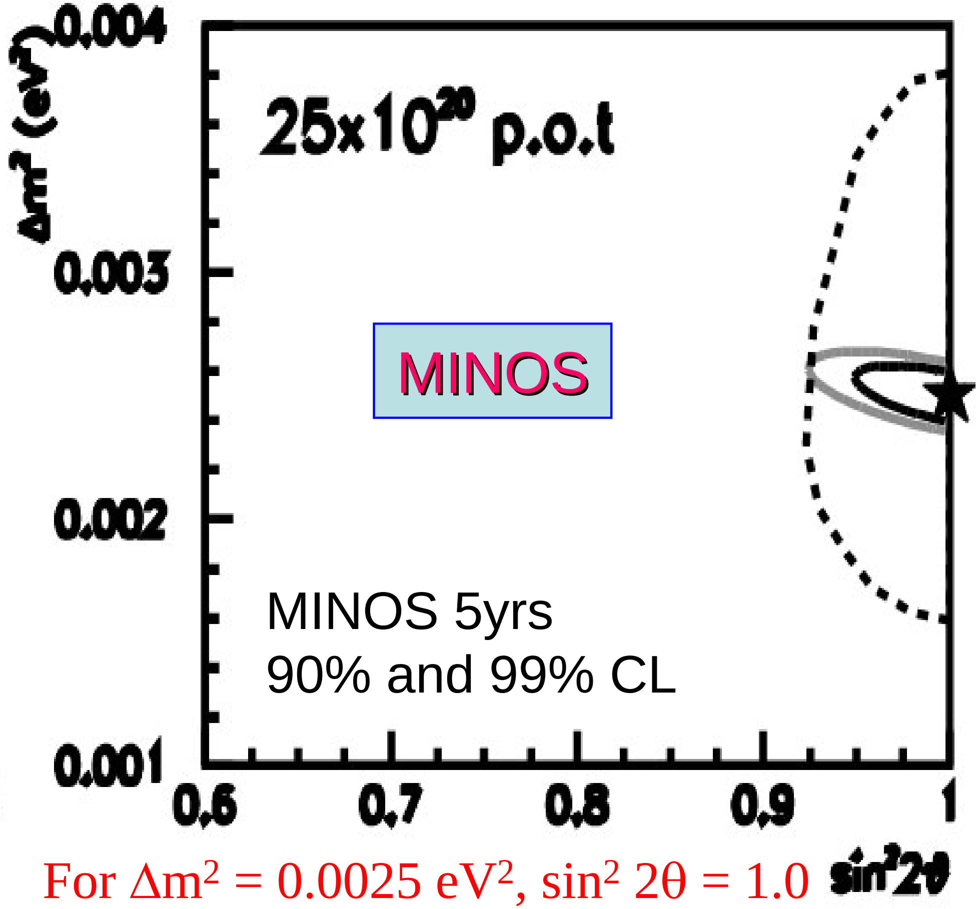
$\Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2$



- Only unknown mixing θ_{13}
  - Only upper bound from CHOOZ reactor exp
  - At the same Δm^2 as ν_μ disapp. → Support 3gen. mix. framework
  - Open possibility to search for CPV ($\theta_{any}=0$ → No CPV)
- Mass hierarchy (sign of Δm^2)
- CPV
- Approaches
  - LBL experiment: Multi purpose (θ_{13}, sign(Δm^2),CPV, θ_{23},$\Delta m_{23}{}^2$)
  - Reactor-based $\bar{\nu}_e$ disappearance: single purpose (θ_{13}), complementary

Expected sensitivites

ν_μ disappearance



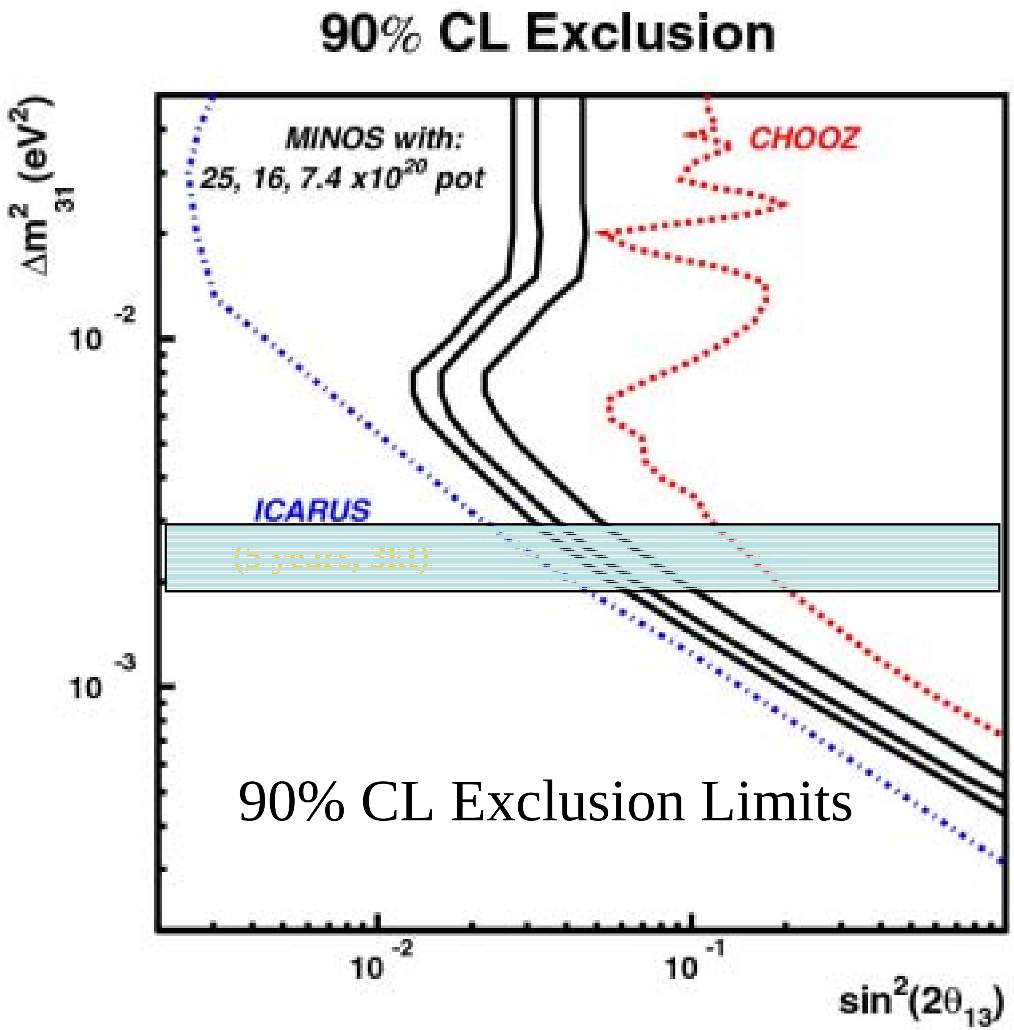
For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta = 1.0$

$\delta(\Delta m^2)$~$2x10^{-4}eV^2$

$\delta(\sin^2 2\theta)$~5%

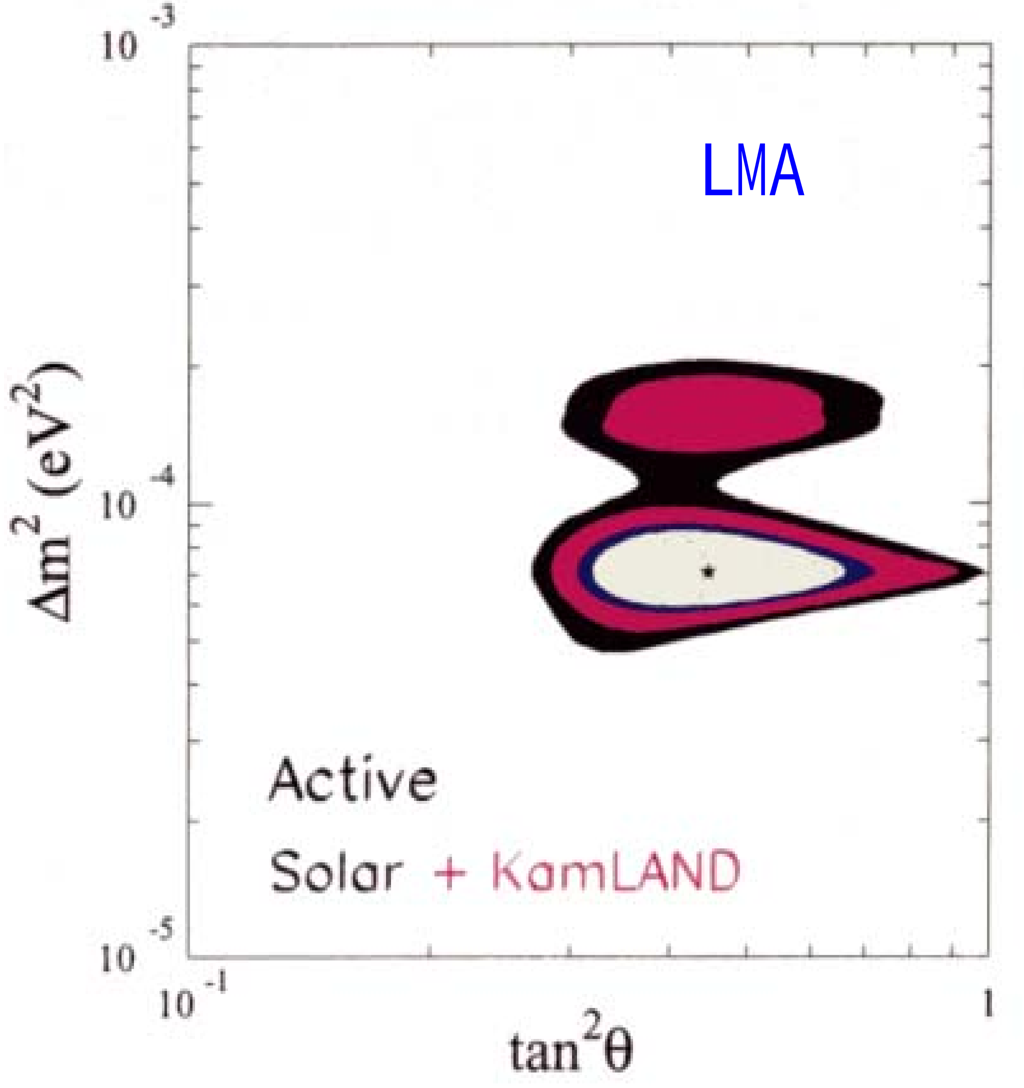
read from above plot

ν_e appearance



ν_e(bar) disappearance (θ_{12}, Δm_{12}^2)

- Combined results of
  - Solar neutrino observations (SK, SNO, ...)
  - Reactor anti-ν observation (KamLAND)
- Large mixing!



J.N. Bahcall et al., J. High Energy Phys. (2003)

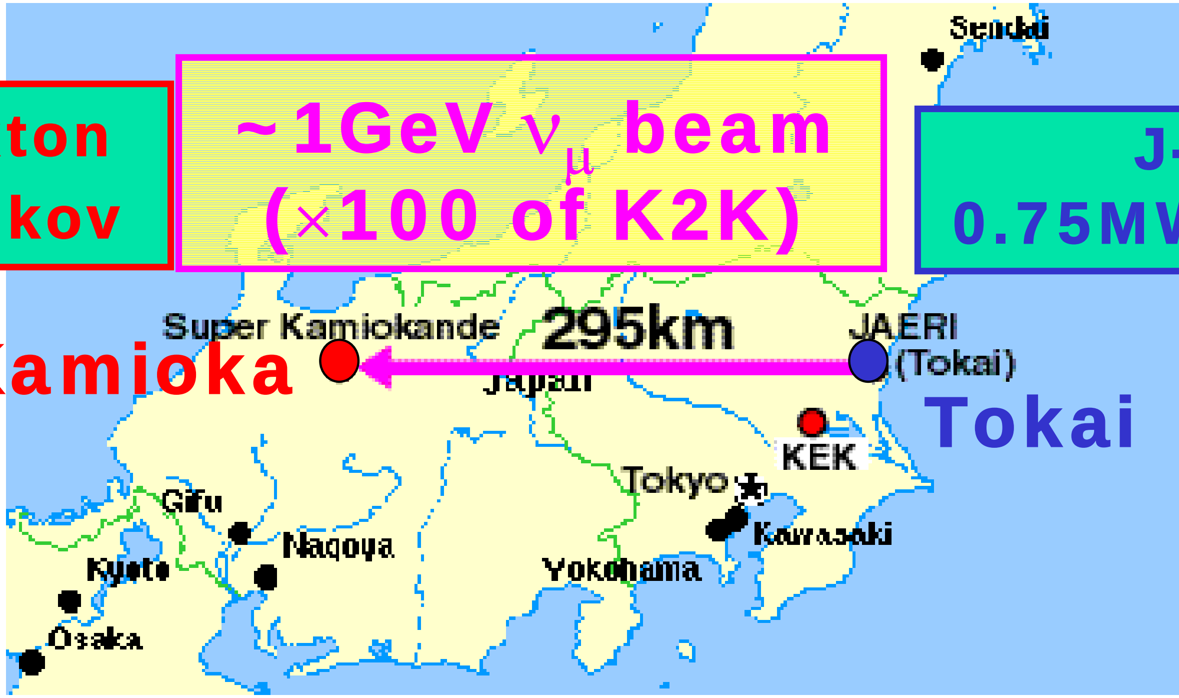
T2K experiment

Long baseline neutrino oscillation experiment from Tokai to Kamioka.

Super-K: 50 kton Water Cherenkov

~1GeV ν_μ beam ($\times$100 of K2K)

J-PARC 0.75MW 50GeV PS



Kamioka

Tokai

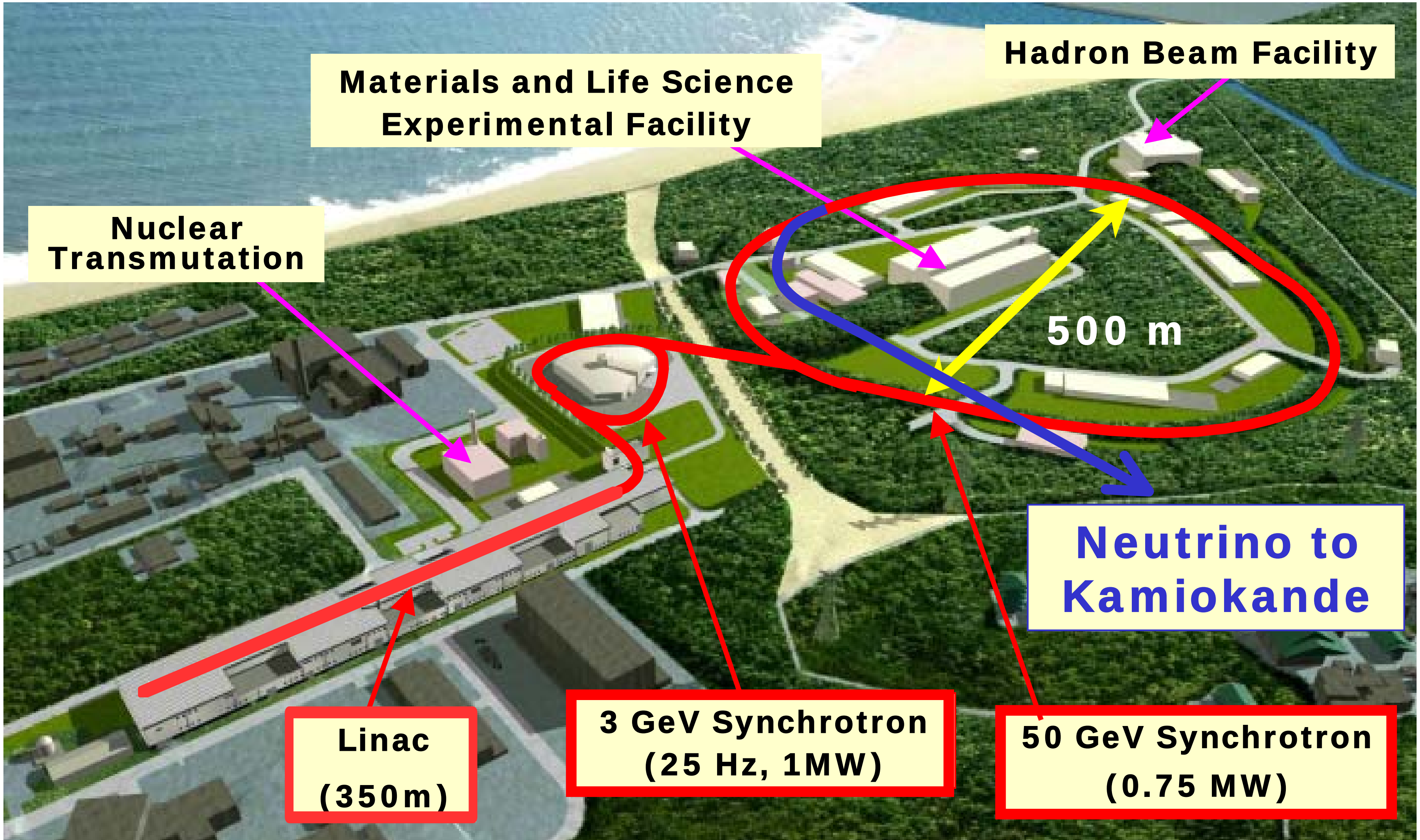
Phase2: Hyper-K

Phase2: 4 MW

Physics motivations

- **Discovery of $\nu_\mu \to \nu_e$ appearance**
- **Precise meas. of disappearance $\nu_\mu \to \nu_x$**
- **Discovery of CP violation (Phase2)**

J-PARC Facility



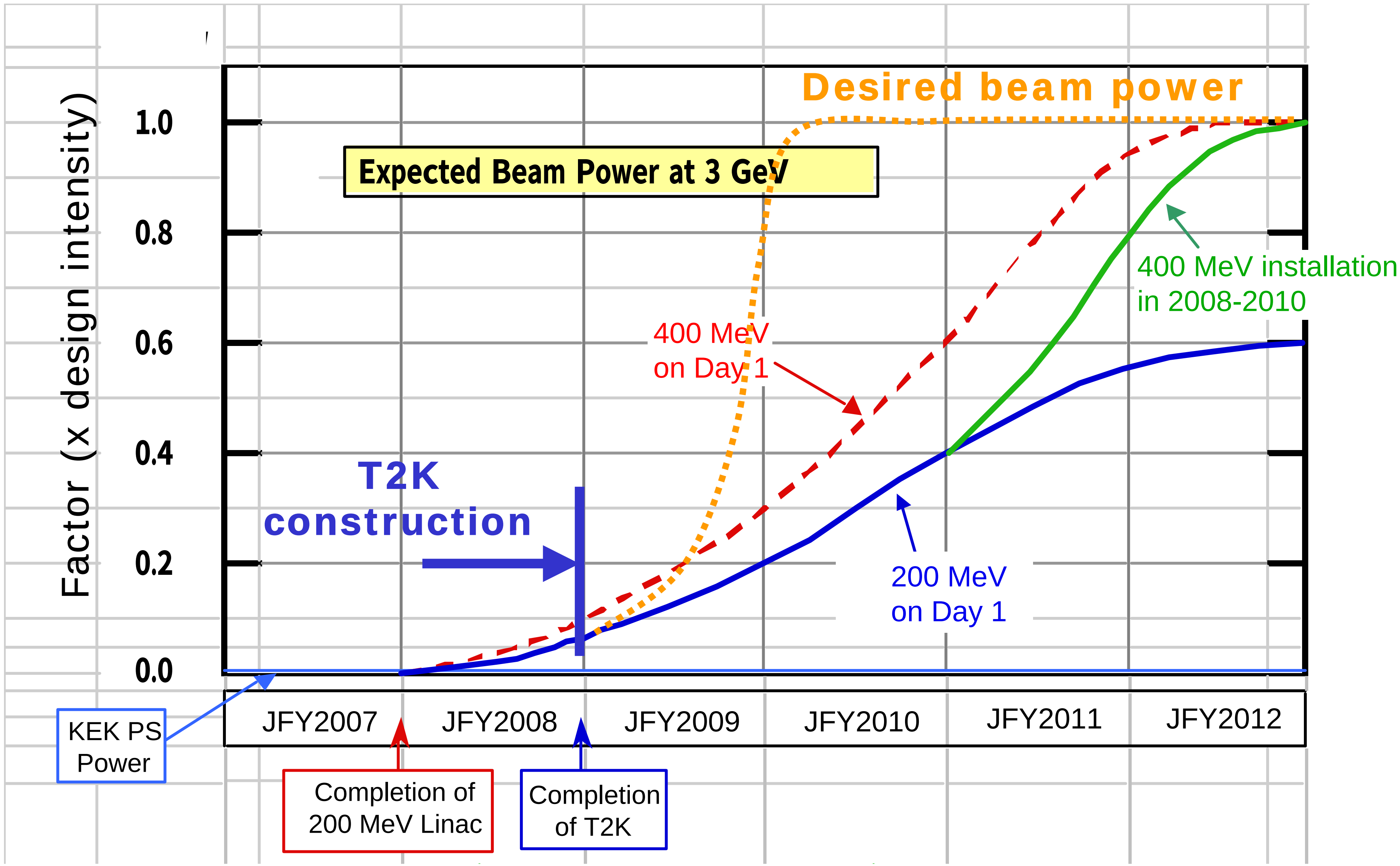
J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAERI

J-PARC status

- Buildings for LINAC and 3GeVPS finished.
- North-east part of tunnel for 50GeVPS finished.
- South-west part of tunnel will finish in FY2006.
- First beam on 50GeV PS in FY2008

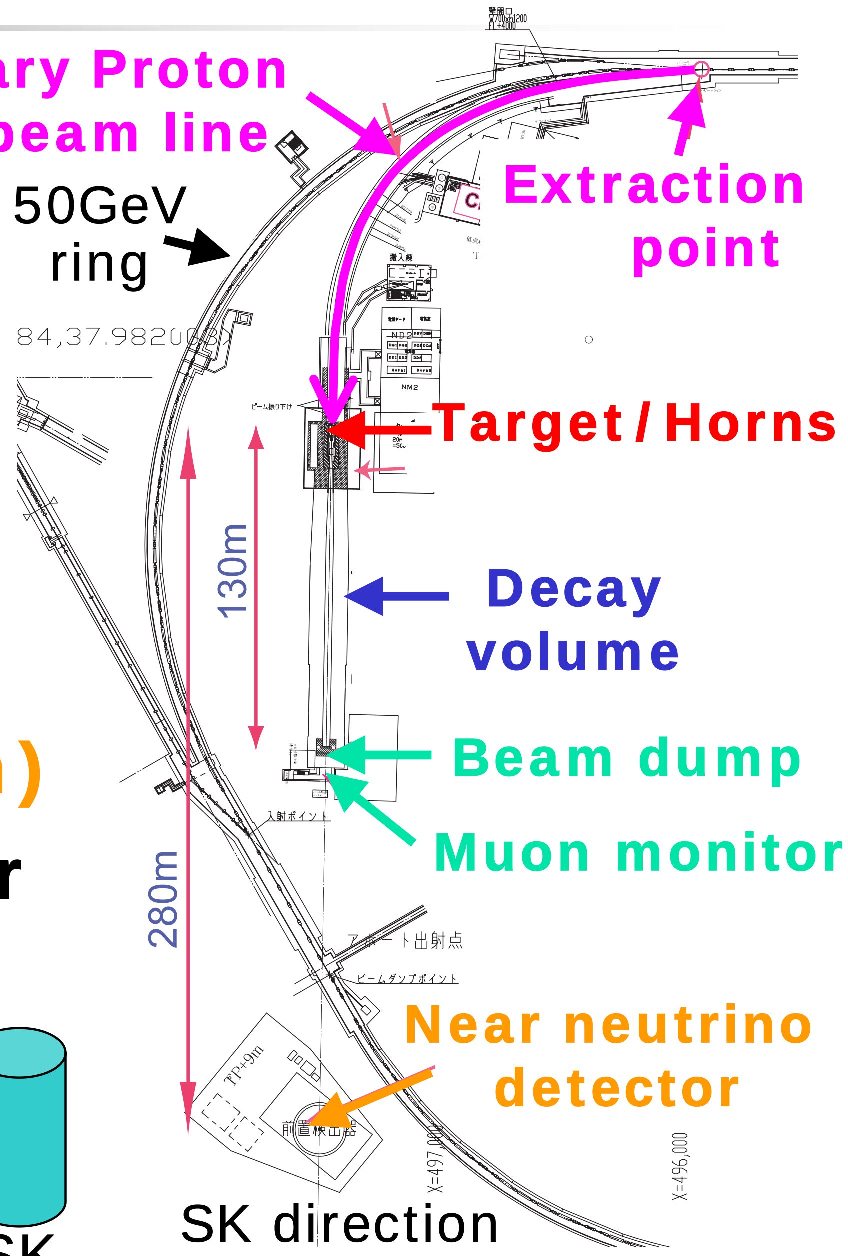
Expected Beam Power

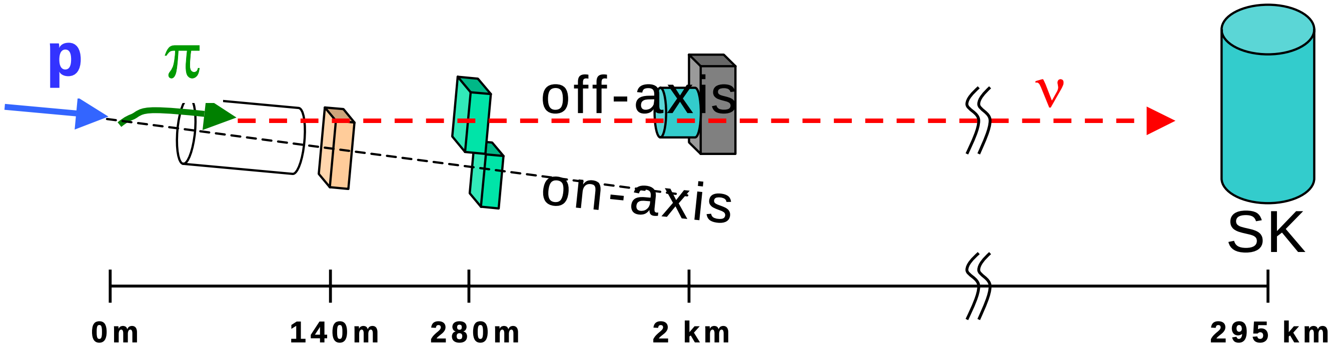


Neutrino facility

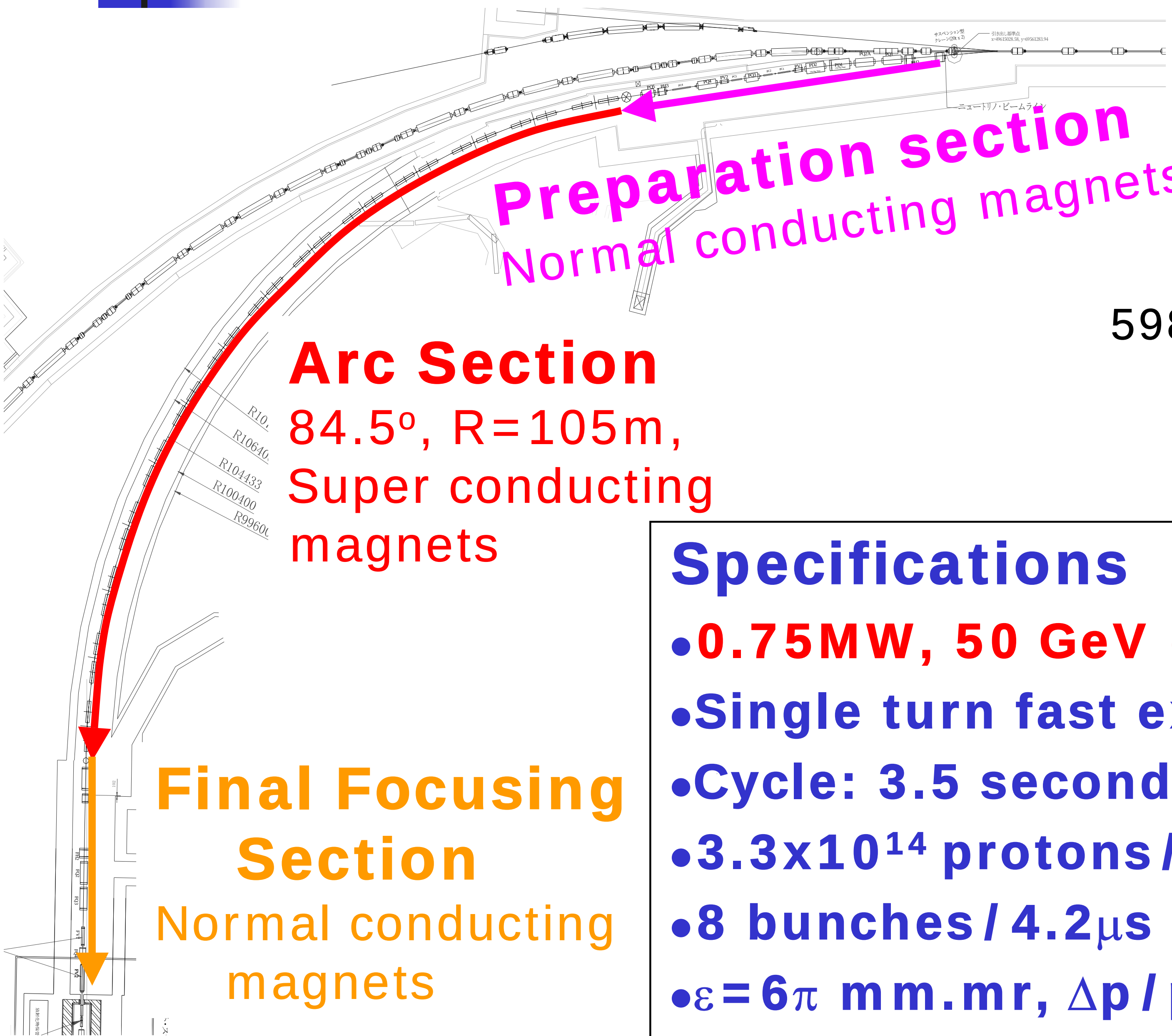
Components

- Primary proton beam line
- Target / Horns
- Decay volume (130m)
- Beam dump
- Muon monitor
- Near neutrino detector (280m)
- Second near neutrino detector (~2km): future option

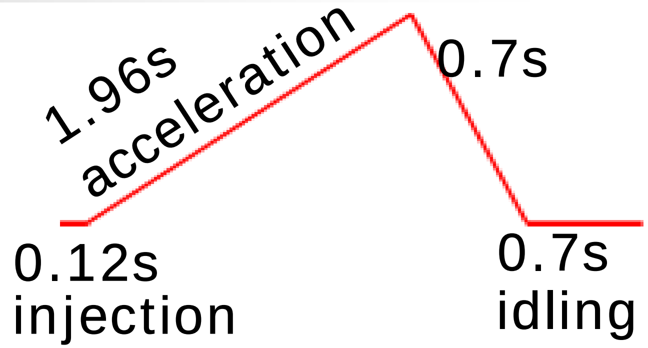


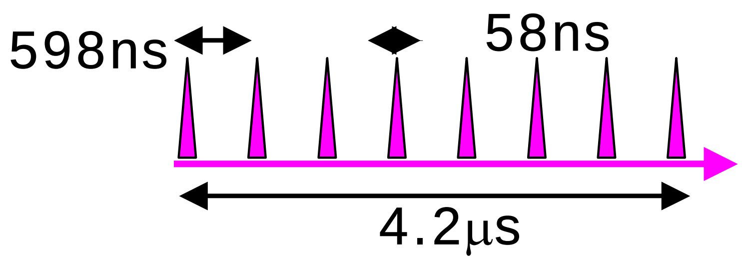


Proton beam line



Target station

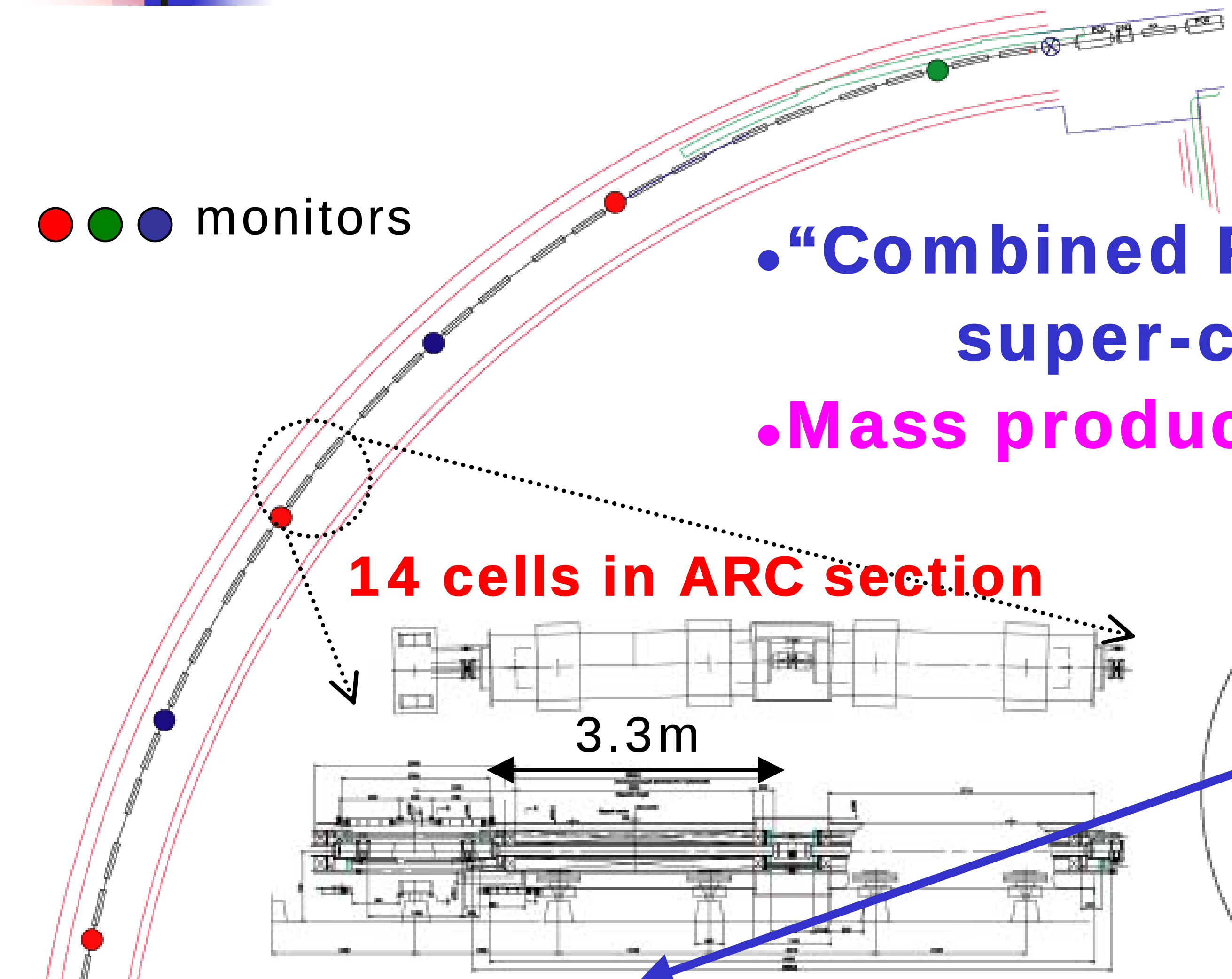




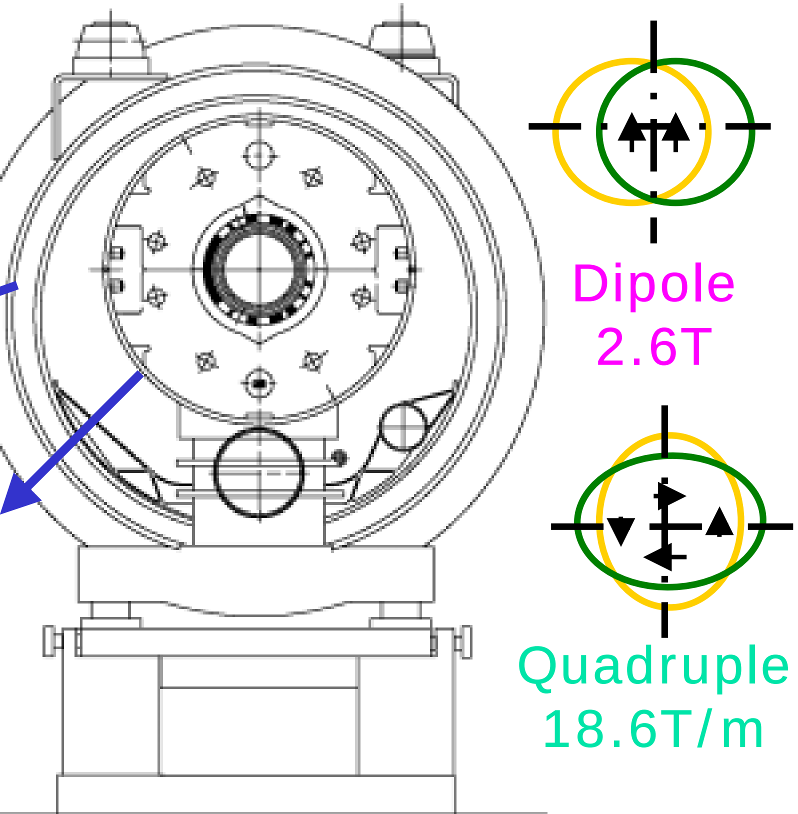
Specifications

- **0.75MW, 50 GeV (40GeV@t=0)**
- **Single turn fast extraction**
- **Cycle: 3.5 second**
- **3.3×10^{14} protons/spill**
- **8 bunches/4.2μs**
- **$\varepsilon=6\pi$ mm.mr, $\Delta p/p=0.31\%$**
  ($\varepsilon=7.5\pi$ mm.mr, $\Delta p/p=0.36\%$@40GeV)

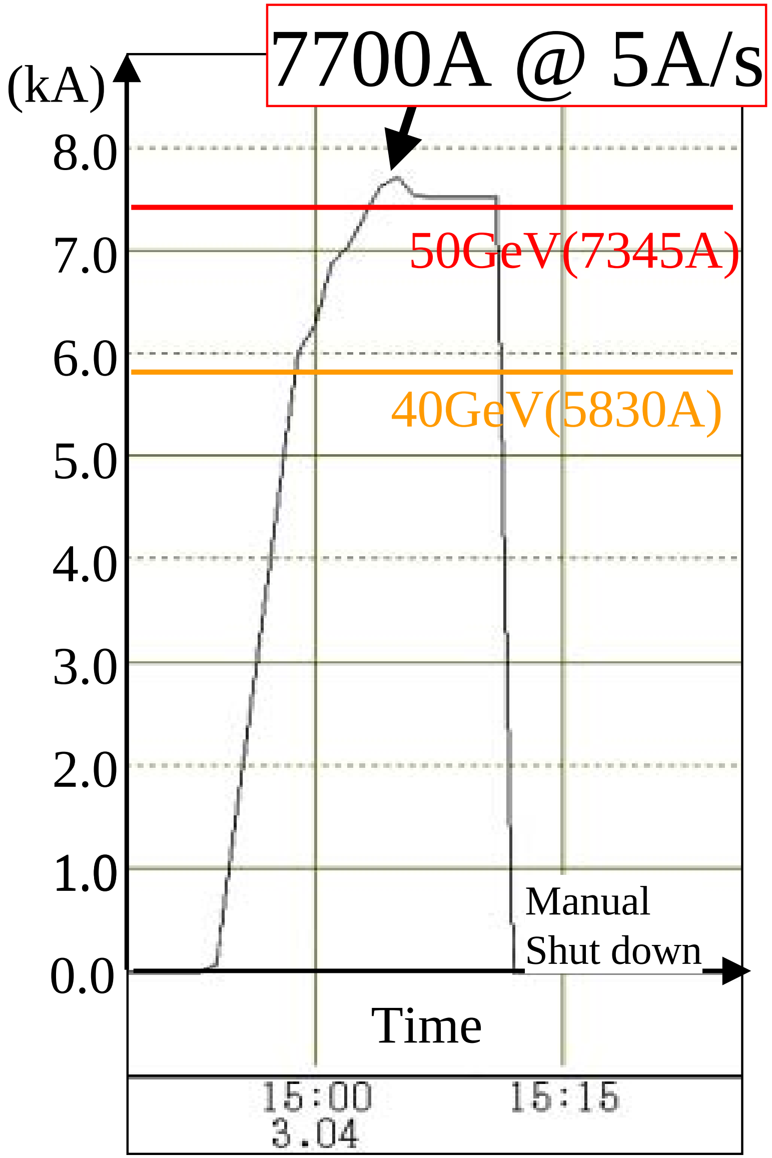
Arc section



- “Combined Function” super-conducting magnets
- Mass production starts soon.

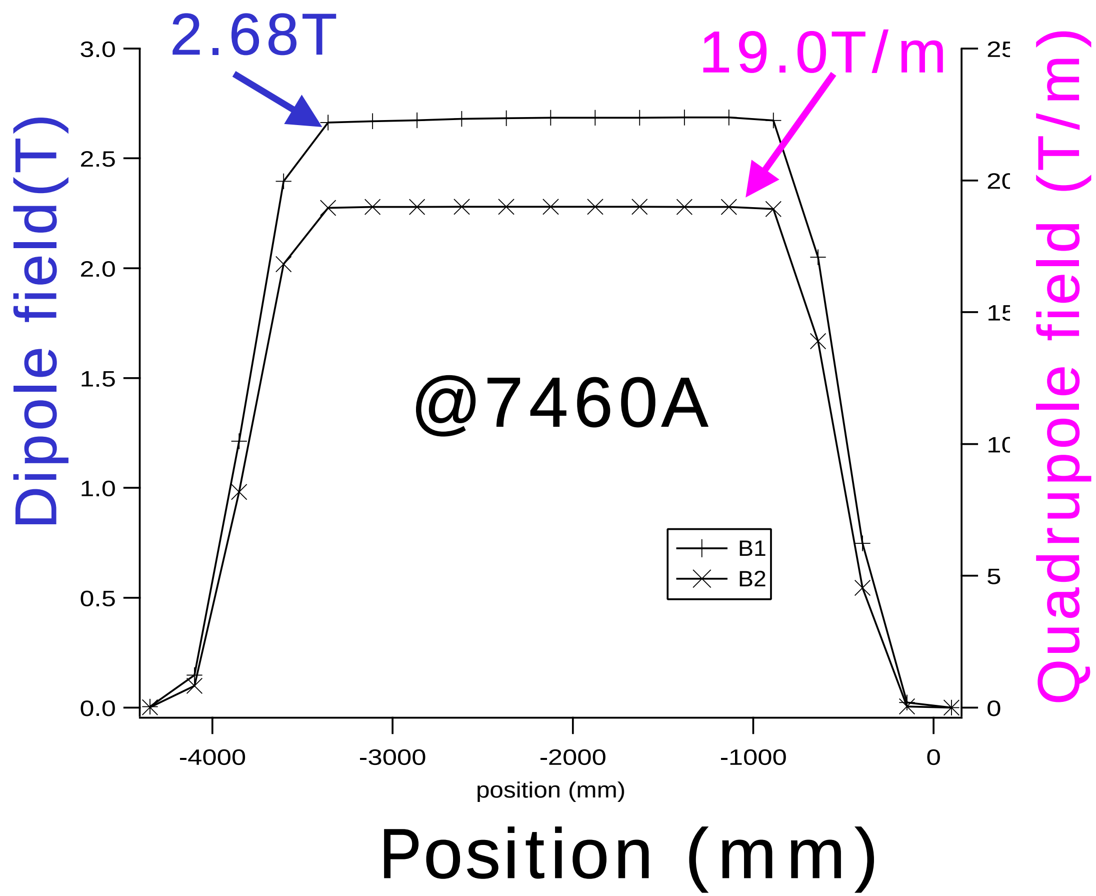


Superconducting magnet

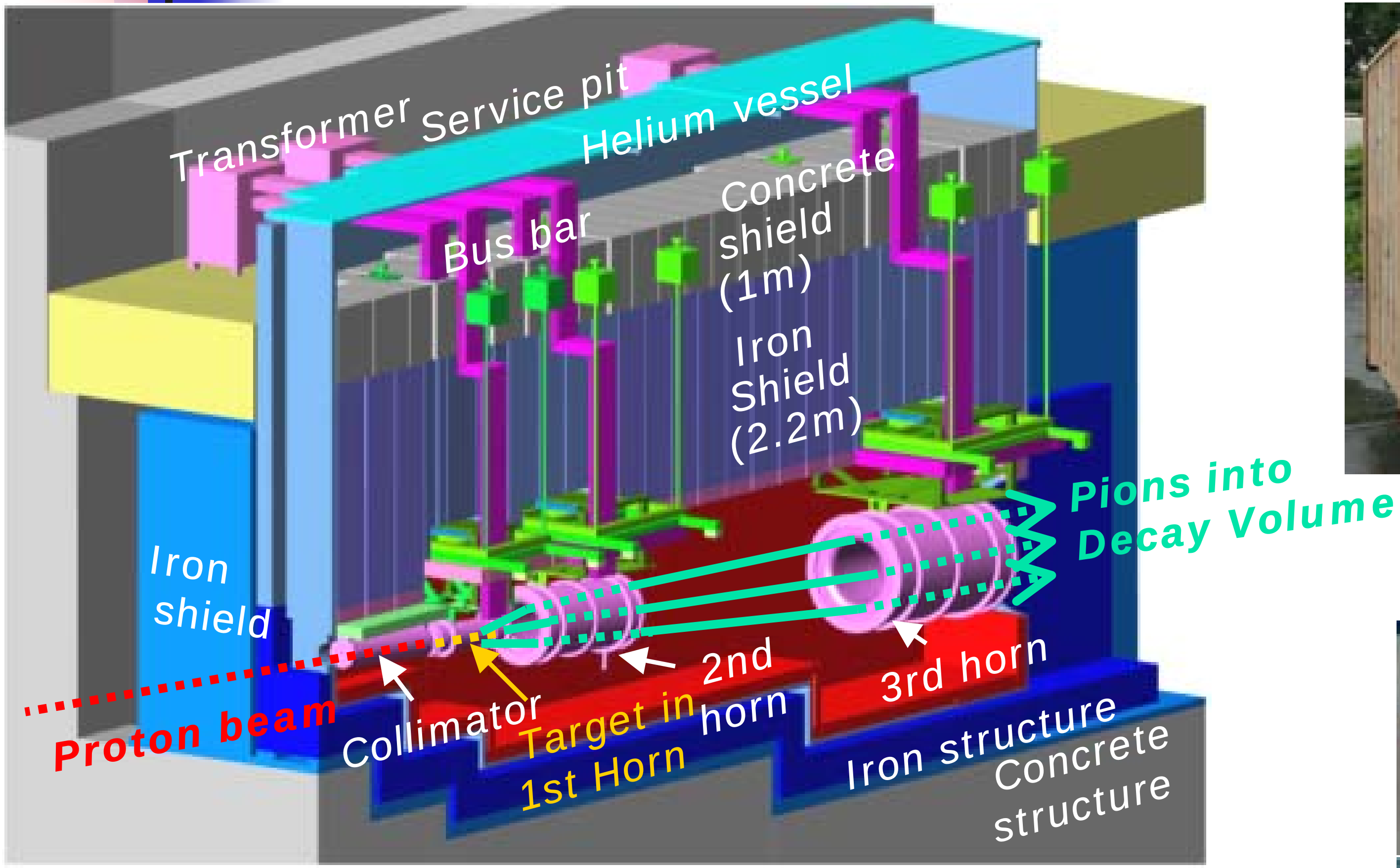


Prototype magnet worked

- **as designed**
- **without quench**



Target and horns



•Prototype inner conductor for 3rd horn

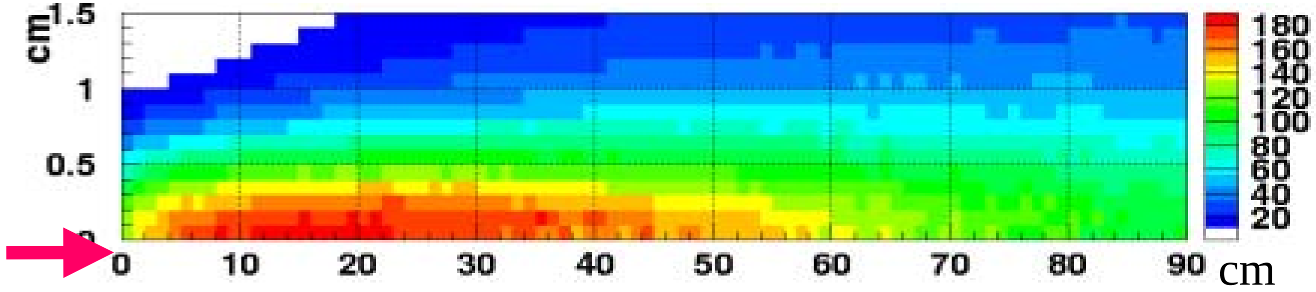
•Prototype inner & outer conductor for 1st horn

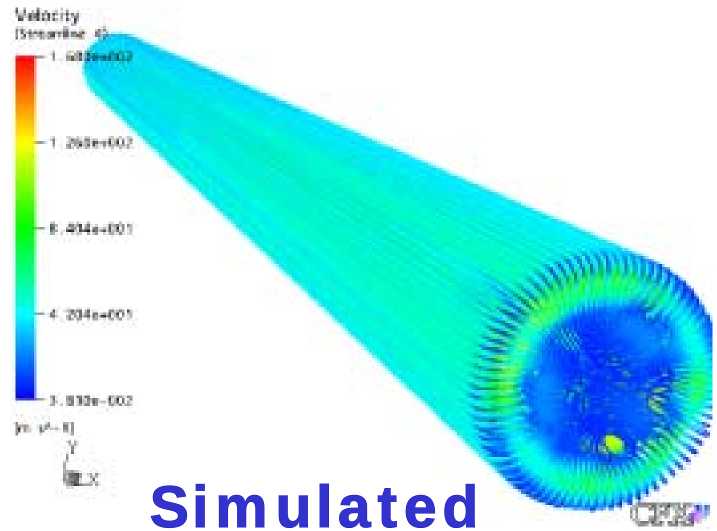
- Graphite target in 1st horn
- 3 horns made with Aluminum
- Water cooling test for horn finished
- 320kA pulse current test in this year

Target

- **Carbon graphite target: 30mm(D)x900mm(L)**
- **2 interaction length (70% int.)**
- **Energy deposit: 58kJ/spill**

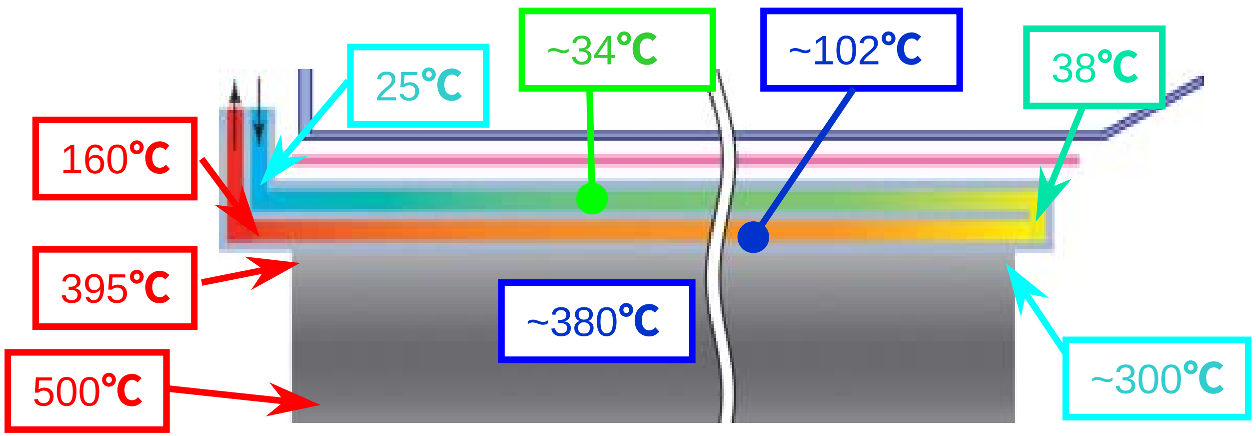
Energy deposit in the target (/ 1 spill)





Simulated streamline of He gas

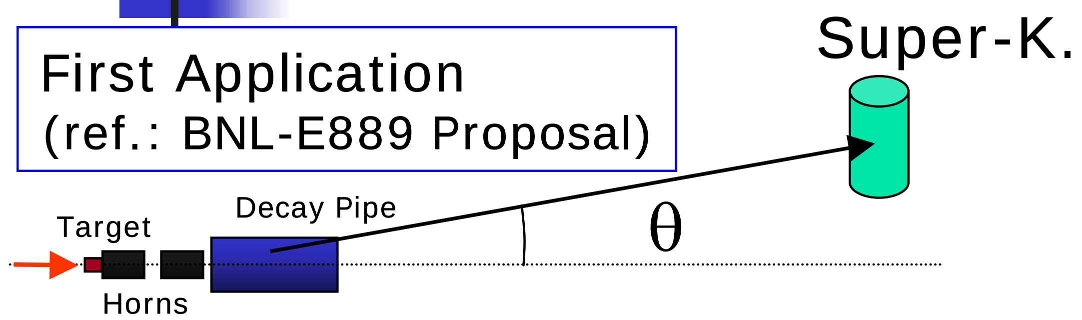
- **Cooled by He gas at outer surface (640W/m^{2}K achieved)**

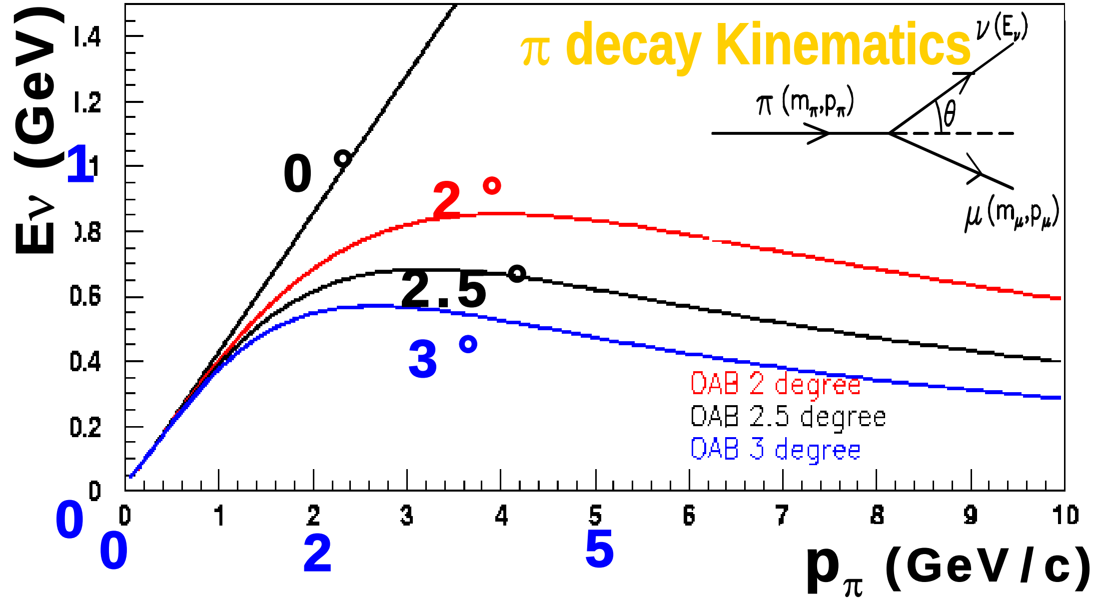


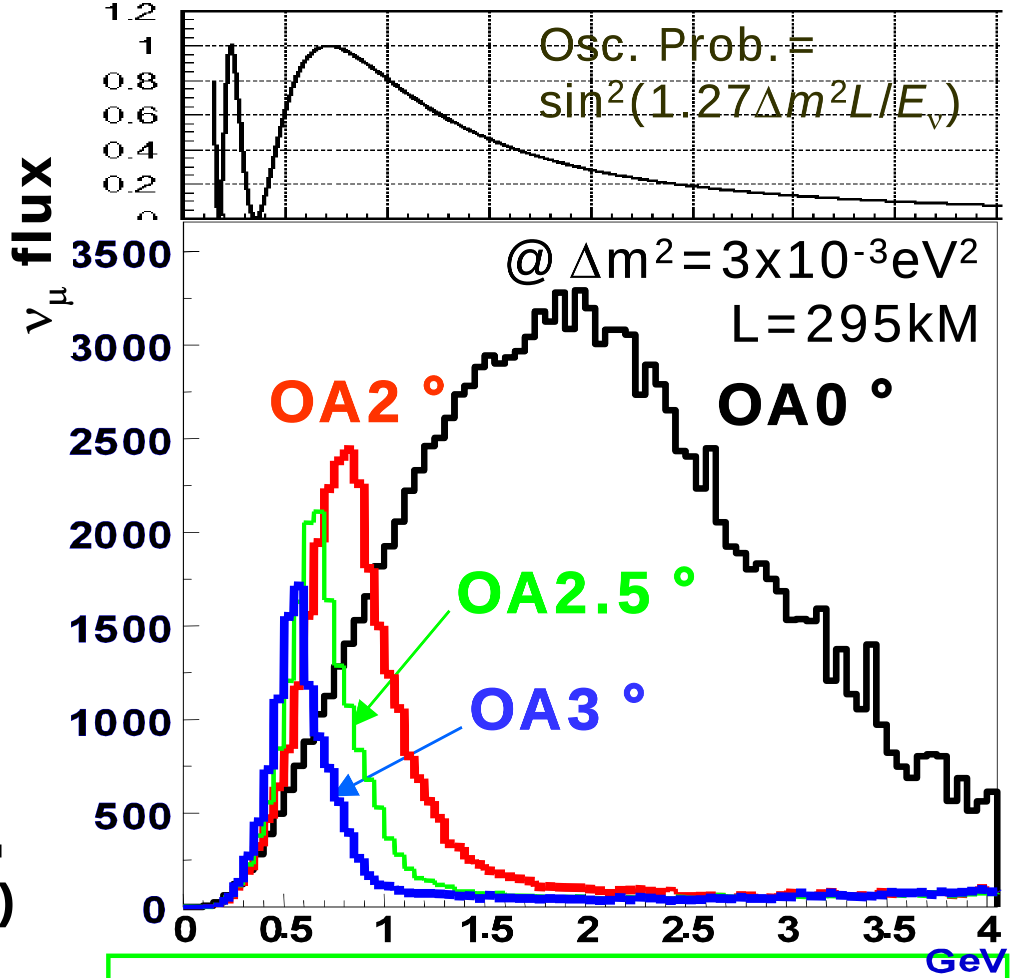
Prototype of target and cooling tube

Off-axis beam

First Application
(ref.: BNL-E889 Proposal)







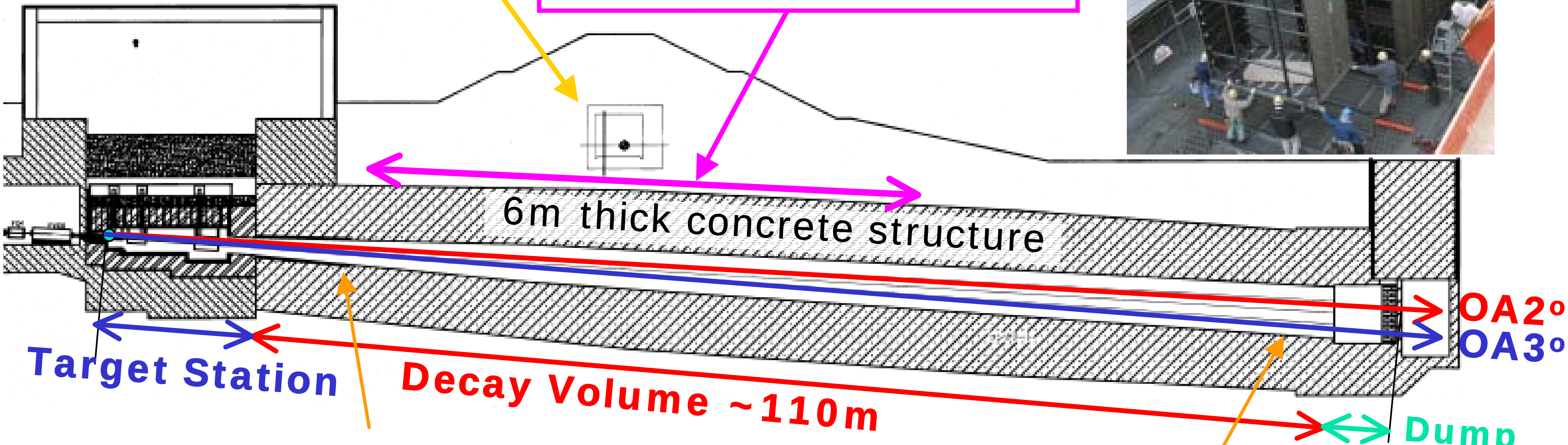
- Detector is intentionally misaligned from WBB axis
- Quasi Monochromatic Beam
- x2~3 intense than NBB
- **Tuned at oscillation maximum**

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

Decay Volume

3NBT (BT bet. 3GeV&MLF)
constructed in 2005

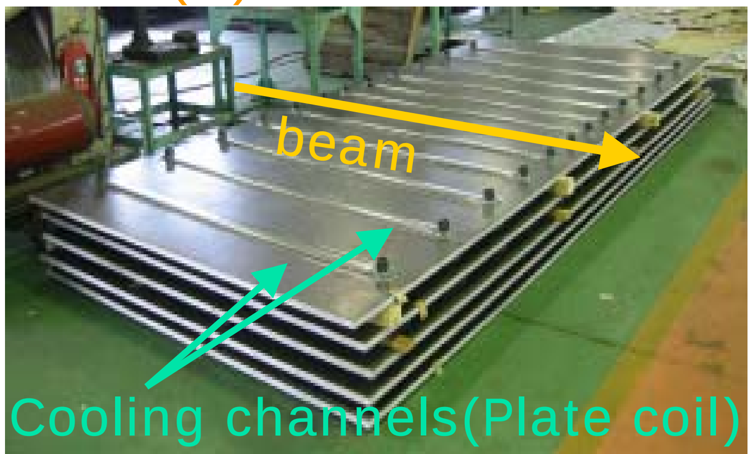
50m Constructed



Cross section:2.2m(W)x2.8m(H)

3.0m(W)x4.6m(H)

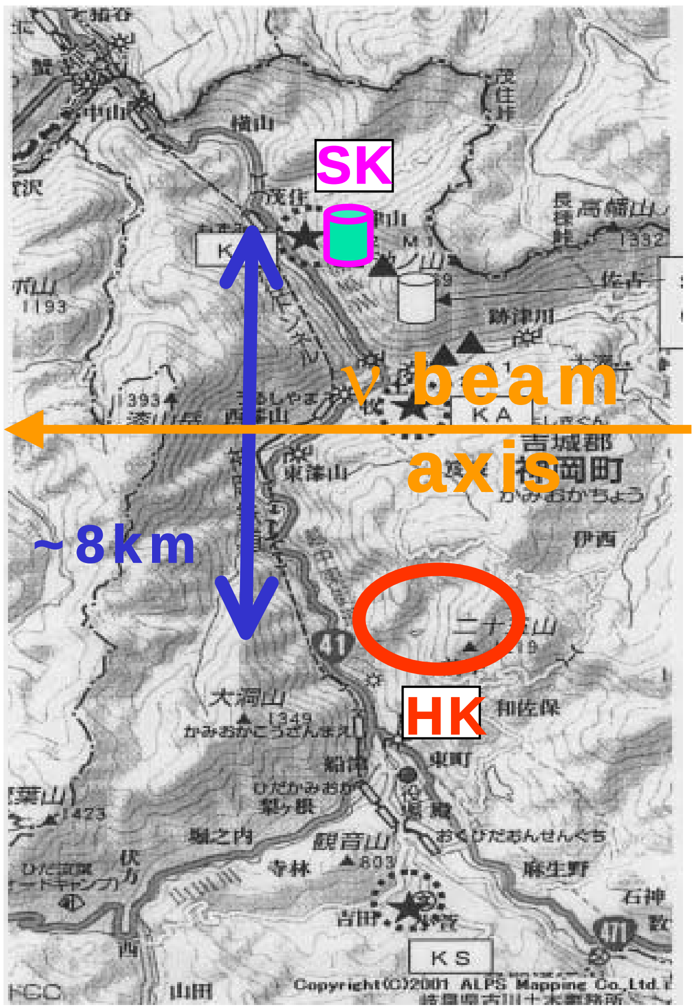
- Cover Off Axis angle : 2°~3°
- Square box shape pipe made with water cooled iron plates (T<60°C at 4MW)
- Filled by 1atm Helium gas



Off-axis beam at SK / HK

Decay pipe

- common Off-axis angle for SK / HK
- covers 2° ~ 3°



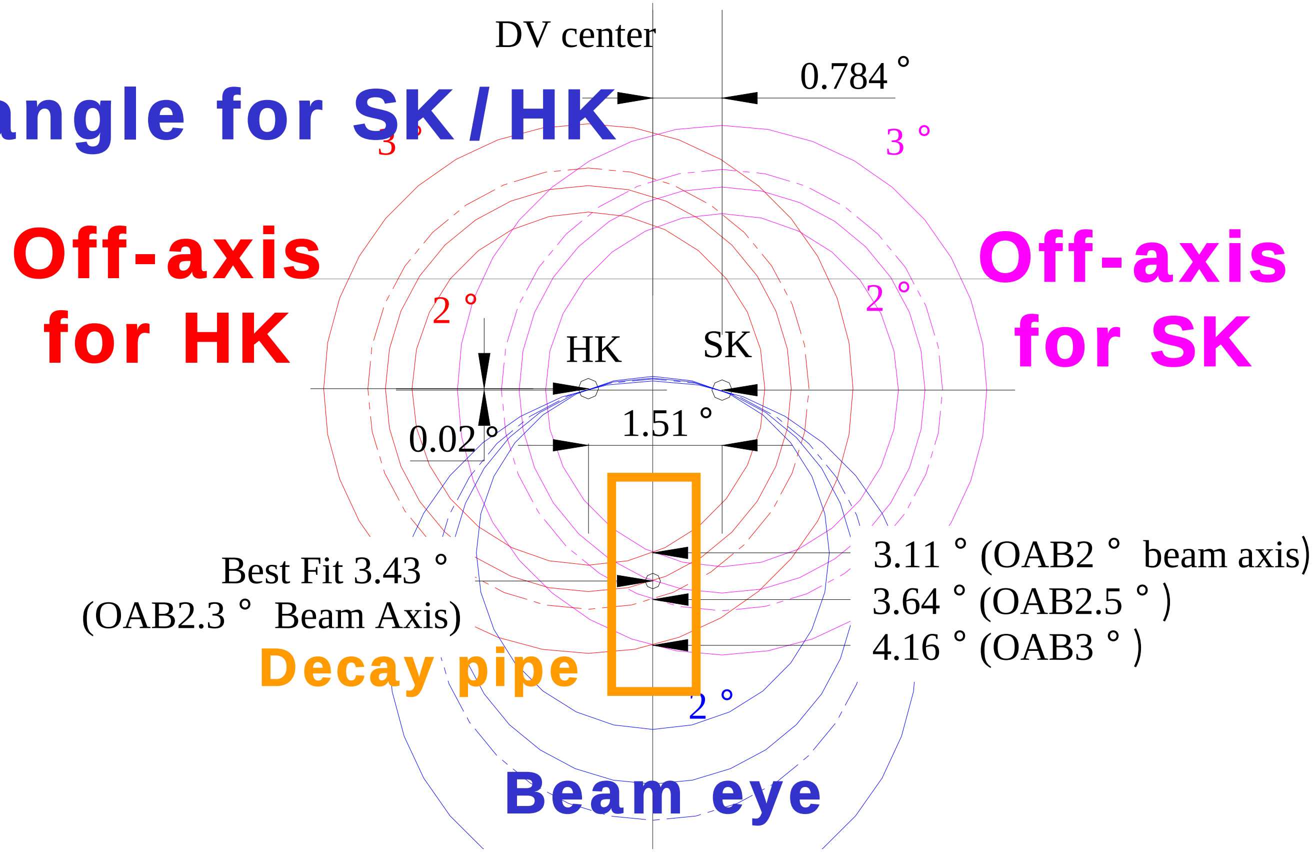


表 3.1: E_ν at the oscillation maximum for the baseline length of 295km and corresponding off-axis angle.

Δm^2 $[10^{-3} eV^2]$	2.04 (90% A.R.)	2.18 (80% A.R.)	2.75 (best fit)	3.17 (80% A.R)	3.28 (90 % A.R)
$E_\nu[GeV]$	0.487	0.520	0.656	0.756	0.782
OA angle[deg.]	3.1	3.0	2.4	2.1	2.0

$\underbrace{3.0 \quad 2.4 \quad 2.1 \quad 2.0}_{\text{Cover this region}}$

Cover this region

Civil construction of DV

Sep. 2, 2004

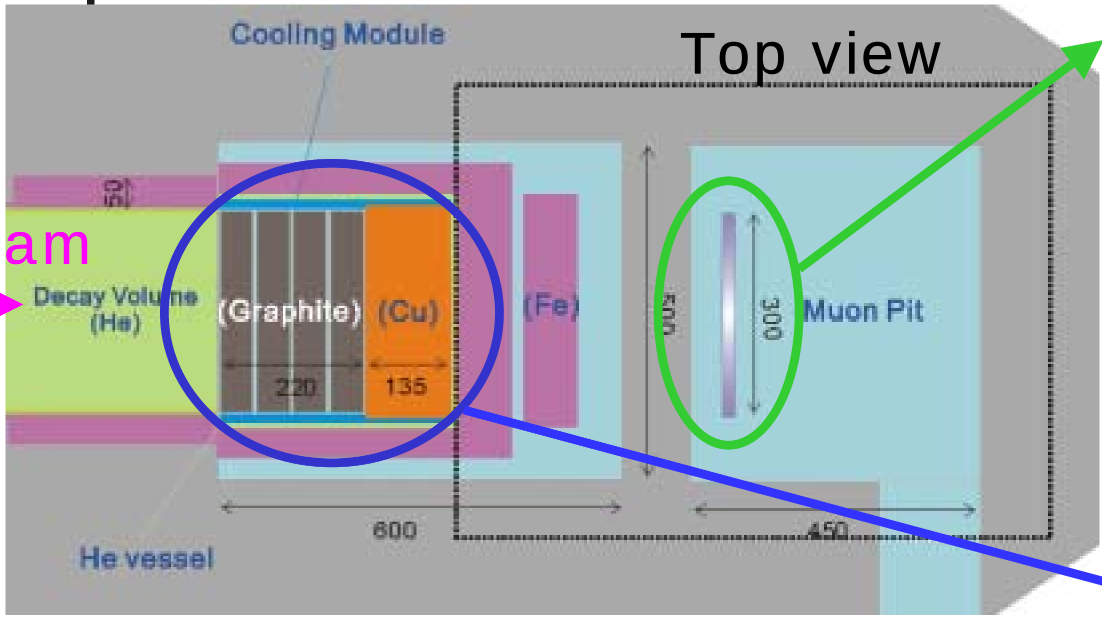
Oct. 26, 2004

Feb. 9, 2005

May 23, 2005

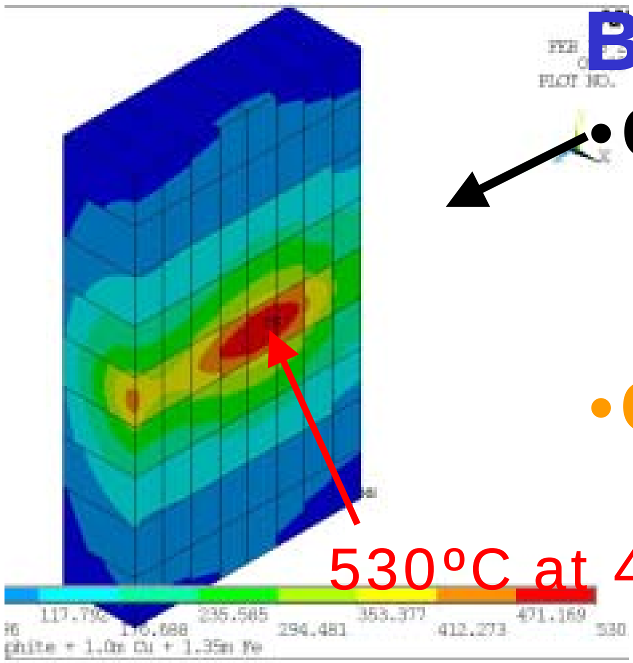
Beam dump & Muon monitor

beam



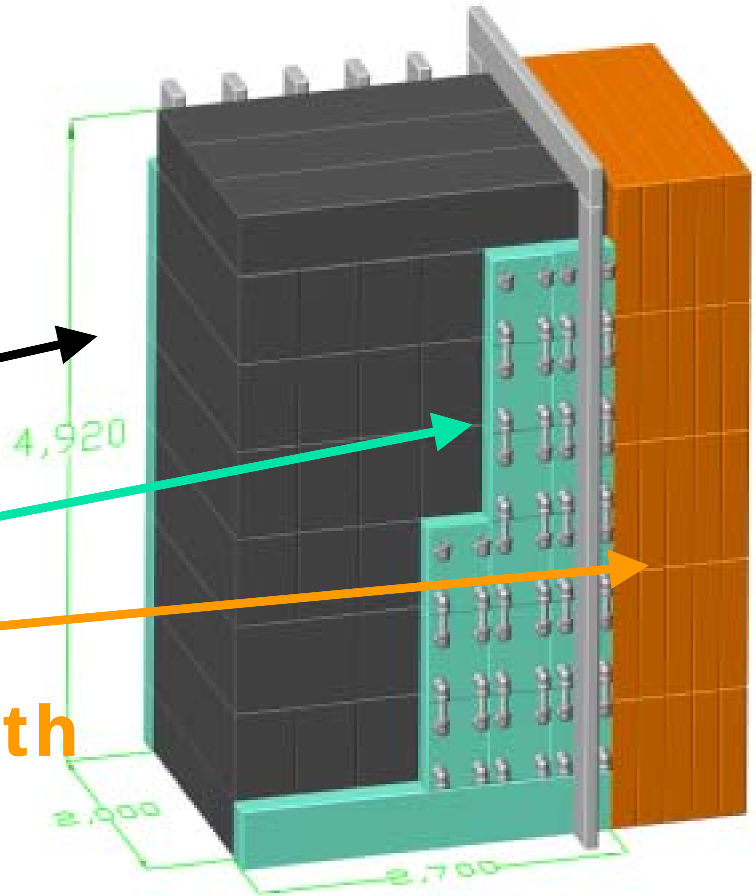
Muon monitors

- spill-by-spill monitor of beam direction / intensity
- Ionization chambers
- Silicon or Diamond Detectors

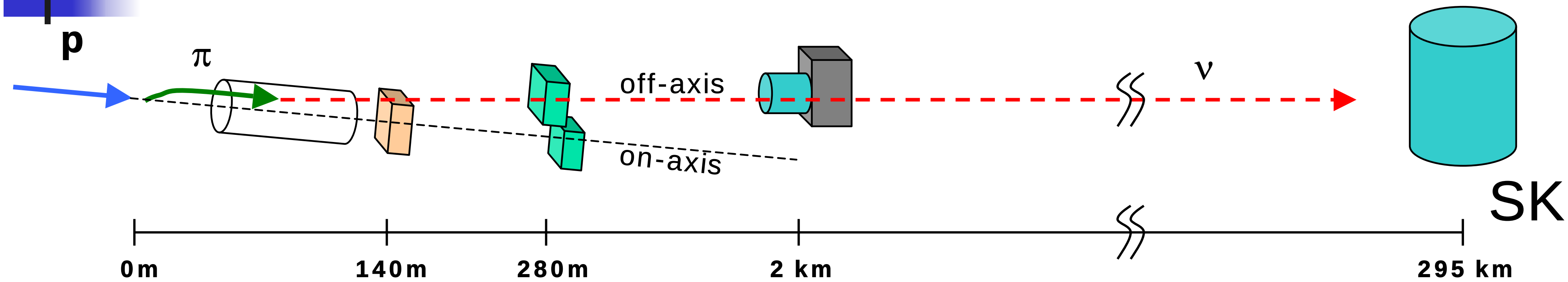


Beam dump

- Graphite blocks with cooling modules
- Copper blocks with cooling path



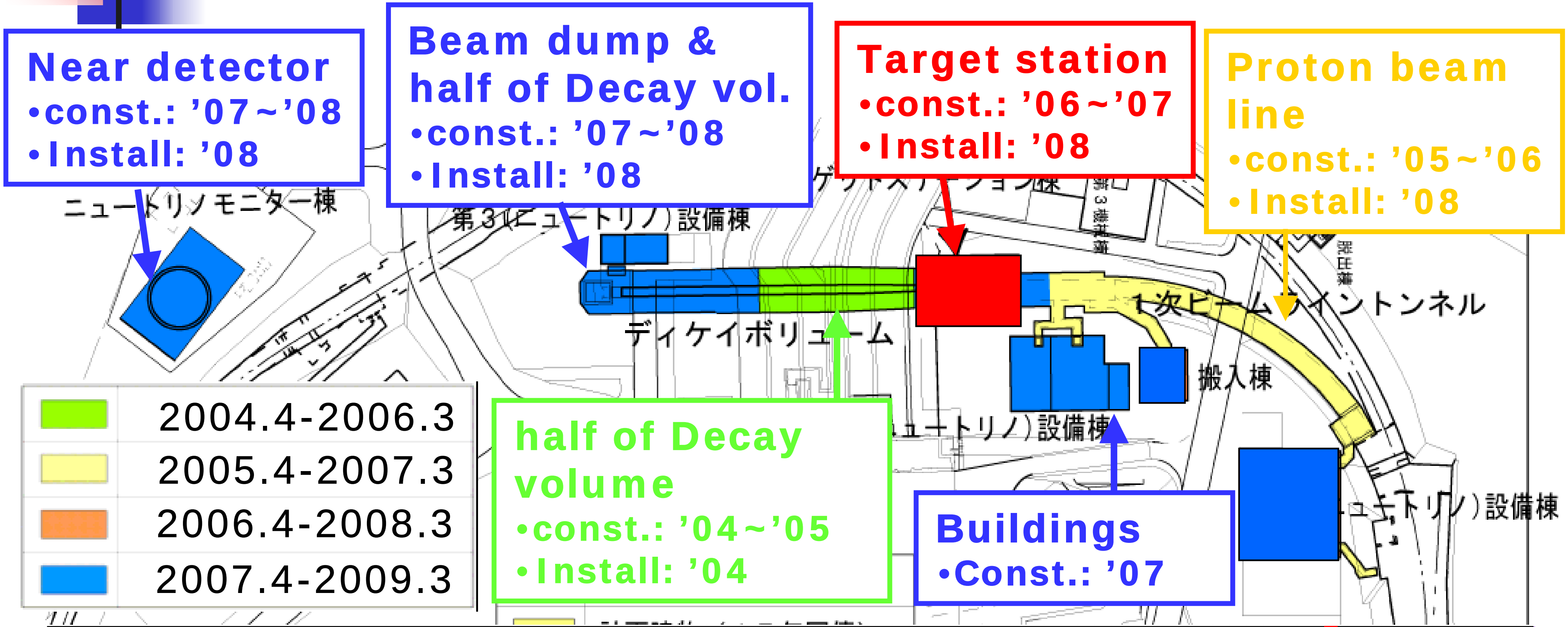
Neutrino detectors



- Near detector @280m
  - Neutrino intensity / spectrum / direction
  - Two detector systems for on and off axis.
- Second Near Detector @2km
  - future option to reduce systematic errors
  - ν_μ energy spectrum and ν_e background study with almost same condition as for SK
- Far Detector @295km: Super Kamiokand

$\Rightarrow$ at session 5 of WG1 on June 23

Schedule of ν beam line



	2004				2005				2006				2007				2008				2009			
	1st yr				2nd yr				3rd yr				4th yr				Last yr				H21			
	4	7	10	1	4	7	10	1	4	7	10	1	4	7	10	1	4	7	10	1	4	7	10	1
Decay Volume I																								
Primary Beam Tunnel																								
1st Util. Build.(NU1)																								
Installation Build.(NC)																								
TS (underground)																								
TS building																								
TS instrumentation/ test operation																								

Start experiment