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FPCP04@Daegu

Toward discovery of θ_{13} and the CPV

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Contents

Introduction

- **Evidences of ν oscillation**
  - Atm ν (SK,1998), confirmed by K2K (2004)
  - Solar ν (SK+SNO,2001), confirmed by KamLAND (2002, 2004)
  - Finite masses!! & Large mixings!!!!! Very much different from quarks
  - First evidence beyond SM
- **Next steps**
  - Understand whole structure of ν mass/mixing
  - How similar/different from quark sector?
    - "Standard" mixing w/ 3x3 matrix?
    - Mass hierarchy?
    - CP violation?

    Would lead physics beyond SM
  - Next generation LBL experiments and reactor exp.
    - w/ High statistics and small systematics
- **New era of precision "Neutrino Flavor Physics"**
  - Cf. Have been done last ~40yrs for quark sector

3 flavor mixing

$$\left|\nu_l\right\rangle = \Sigma U_{li}\left|\nu_i\right\rangle$$ m_i: 3 masses,

Weak Mass eigenstates

Maki-**N**akagawa-**S**akata **Matrix** ($s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$)

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

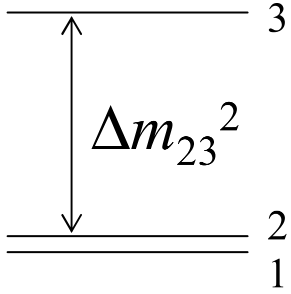
Parameters governing oscillation

3 mixing angles (θ_{12}, θ_{23}, θ_{13})
1 CPV phase (δ)
2 (indep.) mass differences ($\Delta m_{ij}=m_i^2-m_j^2$)

Oscillation probabilities

when $\begin{cases} \Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2 \\ E_\nu / L \approx \Delta m_{23}^2 \end{cases}$ contribution from Δm_{12} is small

(No CPV & matter eff. approx.)



ν_μ disappearance (LBL/Atm) → θ_{23} and $\Delta m_{23}{}^2$

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

ν_e appearance (LBL/Atm) → θ_{13} and $\Delta m_{13}{}^2$

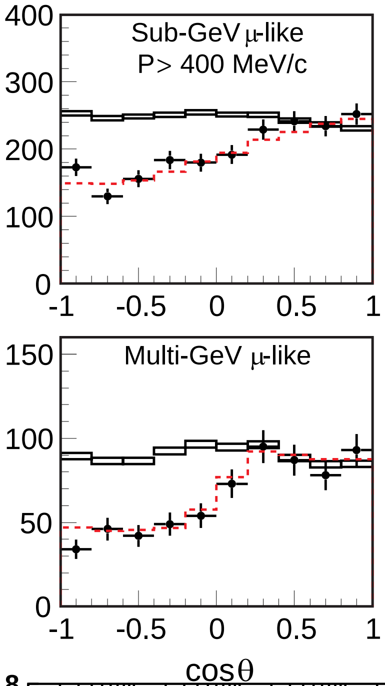
$$P_{\mu \to e} \approx \underbrace{\sin^2 \theta_{23}}_{\sim 0.5} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27 \Delta m_{13}^2 L / E_\nu\right)$$

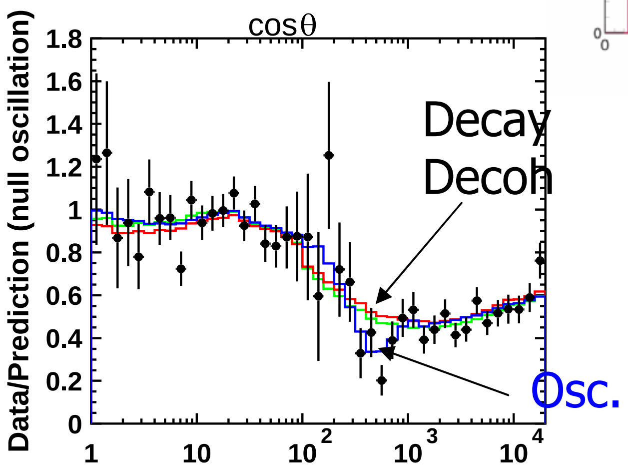
ν_e disappearance (Reactor) → Pure θ_{13} and $\Delta m_{13}{}^2$

$$P_{e \to x} \approx 1 - \underbrace{\sin^2 2\theta_{13}}_{\ll 1} \cdot \sin^2\left(1.27 \Delta m_{13}^2 L / E_\nu\right)$$

Results from atm & acc. ν_μ disapp.(θ_{23},Δm_{23}^2)

SK Atm ν



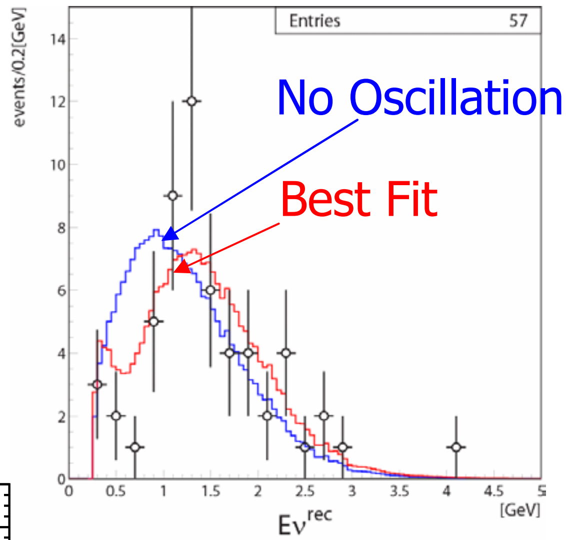


T.Kobayashi (KEK)

K2K ν_μ disapp.

Deficit of ν_μ events

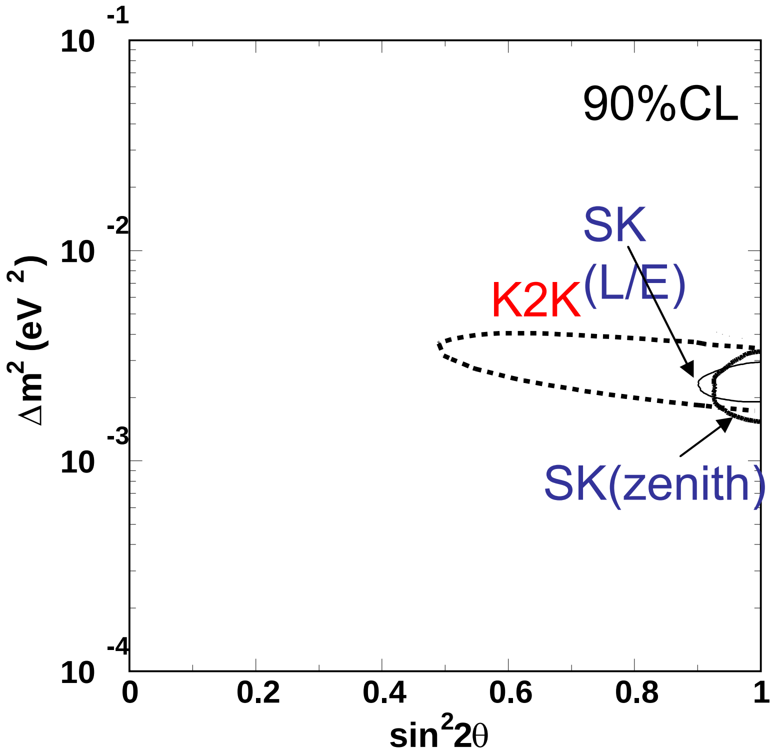
- Obs: 107
- Exp'ed: $150.9^{+11.5}_{-10.1}$



Significance

- # of events: 3σ
- Spectrum : 2.6σ
- **Combined : 4σ**

Allowed parameter region

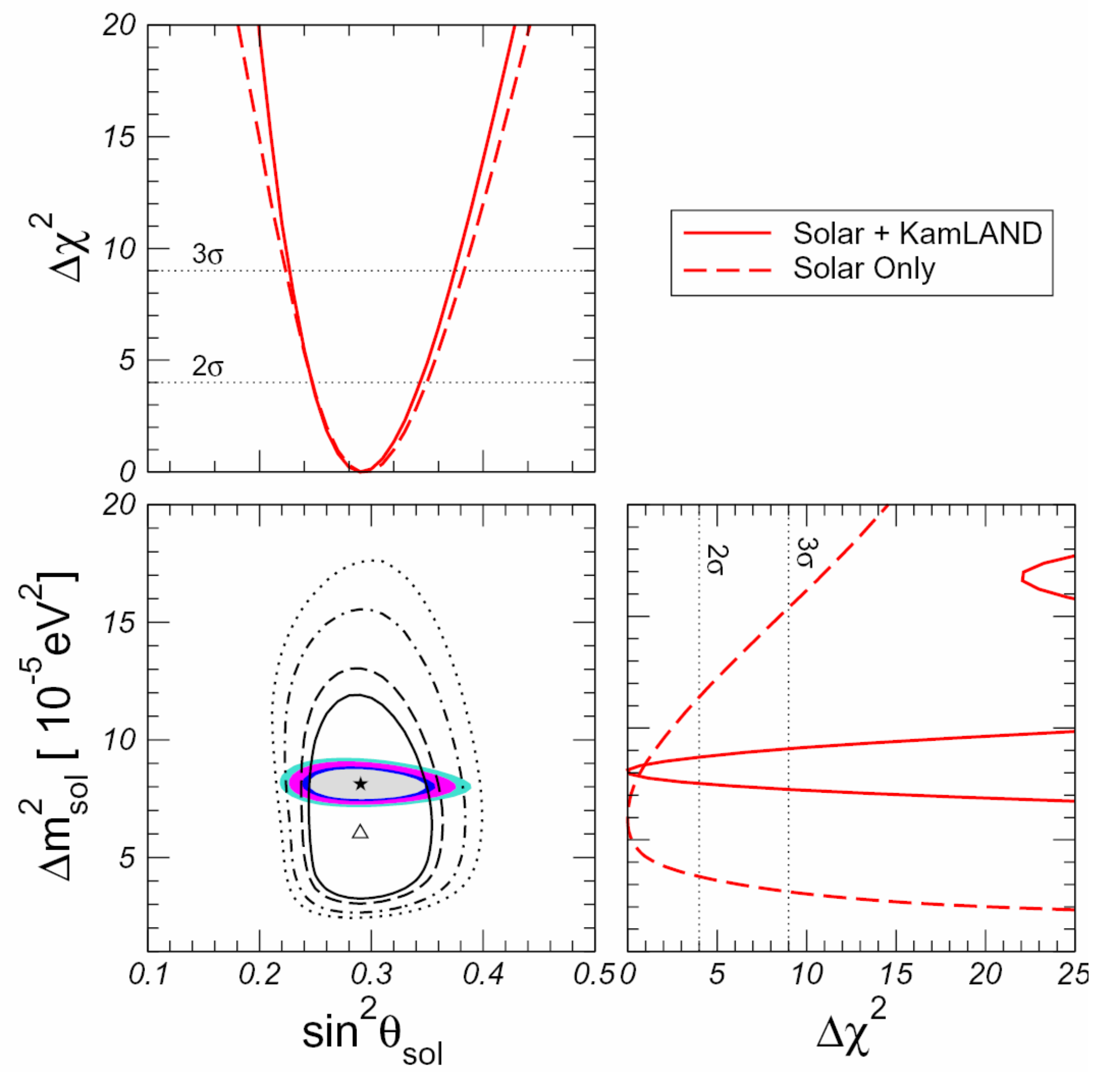


$\sin^2 2\theta > 0.92$ (SK L/E)

$\Delta m^2 = 1.9 \sim 3.0 \times 10^{-3}$eV (SK Zen.)

Results from solar(ν_e) & reactor($\bar{\nu}_e$) (θ_{12},Δm_{12}^2)

- Solar neutrino observations
  - SK, SNO
    $\nu_e \rightarrow \nu_\mu,\nu_\tau$
- KamLAND
  - Reactor $\bar{\nu}_e$ disappearance
  - Few MeV x ~200km

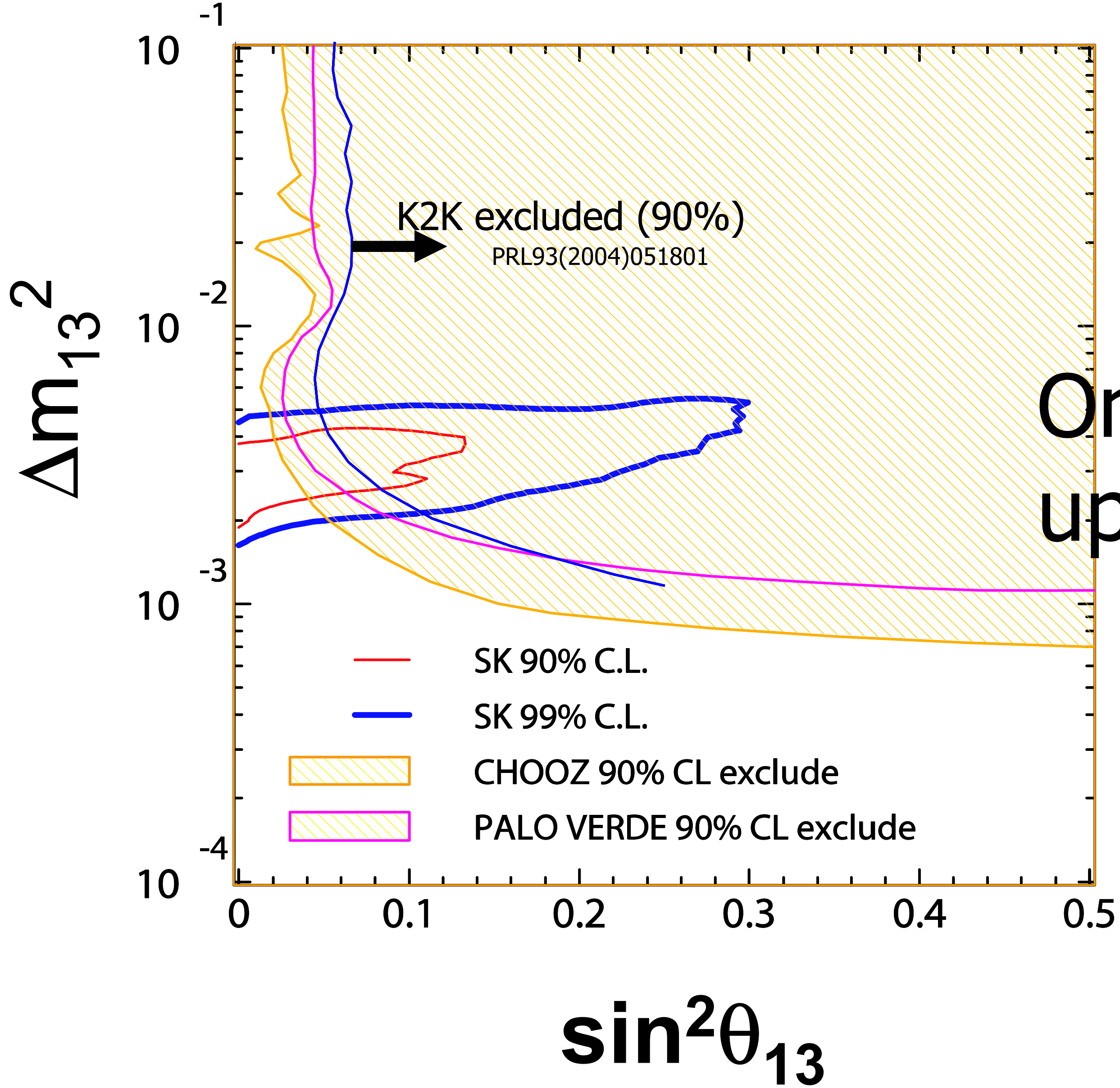


Global (solar+KamLAND)
Best fit
$\sin^2\theta_{sol}$ = 0.29 (θ_{sol}=32.6^o)
Δm_{sol}^2 = 8.1x10^{-5}eV^2

3σ region:
0.23<$\sin^2\theta_{sol}$<0.37
(28.7^o<θ_{sol}<37.5^o)
Δm_{sol}^2=7.3~9.1x10^{-5}eV^2

M.Maltoni, hep-ph/0405172v3 (incl. ν'04 data)

Latest constraint on θ_{13}

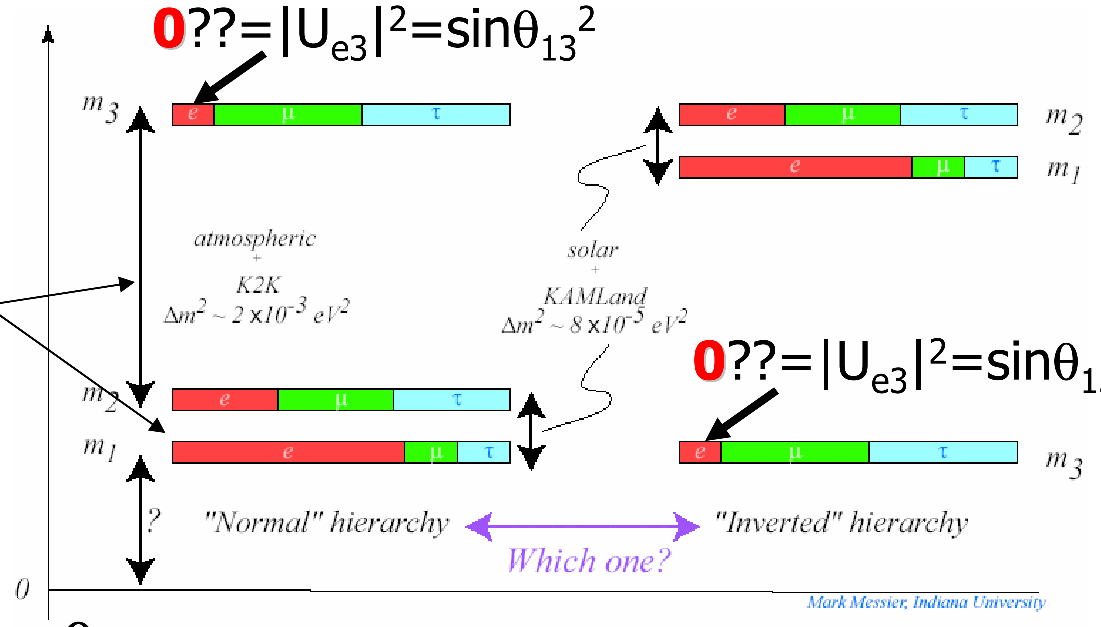


Only upper limit

Kajita, NOW'04

Present knowledge and What's next?

θ_{12}~33° Δm_{12}^2~0.00008eV²
θ_{23}~45° Δm_{23}^2~0.0025eV²
θ_{13}<10° ($\Delta m_{13}^2 \sim \Delta m_{23}^2$)?
δ ???



- Only unknown mixing θ_{13} (and really $\Delta m_{13}^2 \sim \Delta m_{23}^2$?)
- Mass hierarchy (sign of Δm^2)
- CPV
- Approaches
  - LBL experiment: Multi purpose (θ_{13}, sign(Δm^2),CPV, θ_{23},Δm_{23}^2)
  - Reactor-based $\bar{\nu}_e$ disappearance: single purpose (θ_{13}), complementary

$\nu_\mu \rightarrow \nu_e$ appearance and CPV

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\,(1 - 2S_{13}^2)\right)$$ Main

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$ CP-odd

$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$ Solar

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1 - 2S_{13}^2)$$ Matter

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

Matter eff.: $a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$

$$A_{CP} \equiv \frac{P - \bar{P}}{P + \bar{P}} \approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

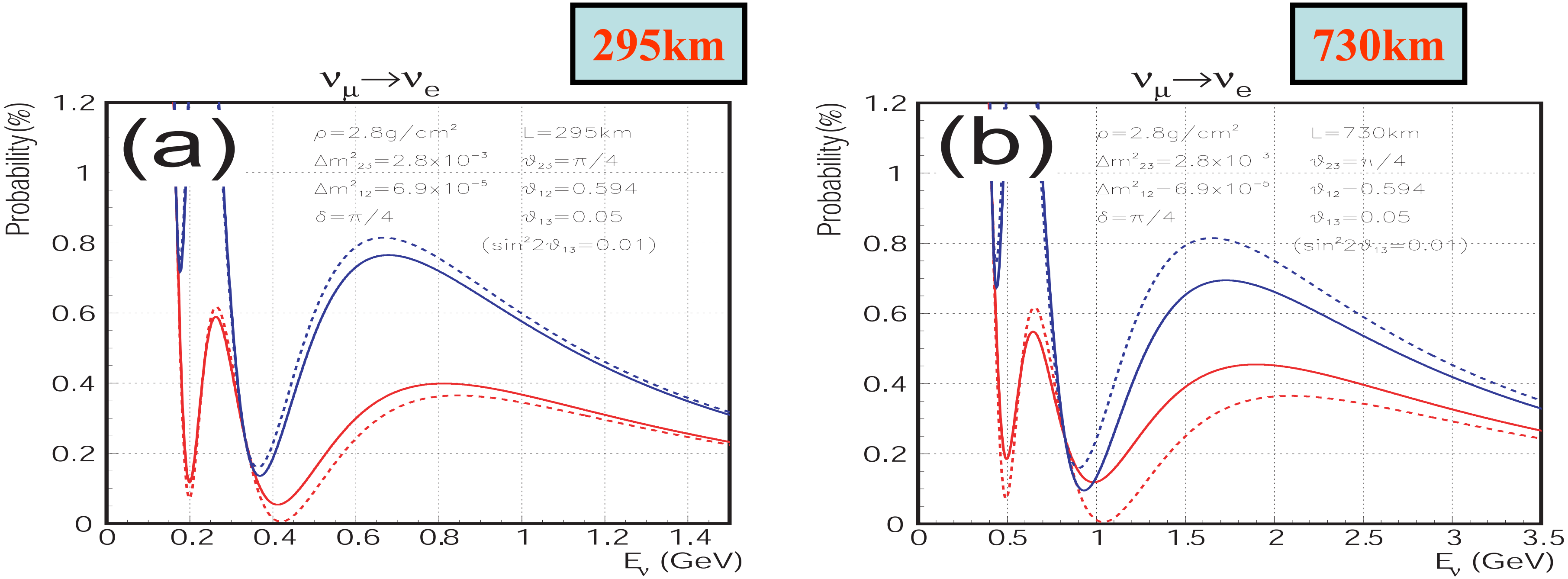
$N(\nu_e) \propto \sin^2 2\theta_{13}$; $A_{CP} \propto \frac{1}{\sin\theta_{13}}$

Size of θ_{13} critical !

CPV vs matter effect

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

$$P \equiv P(\nu_\mu \rightarrow \nu_e)$$
$$\bar{P} \equiv P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

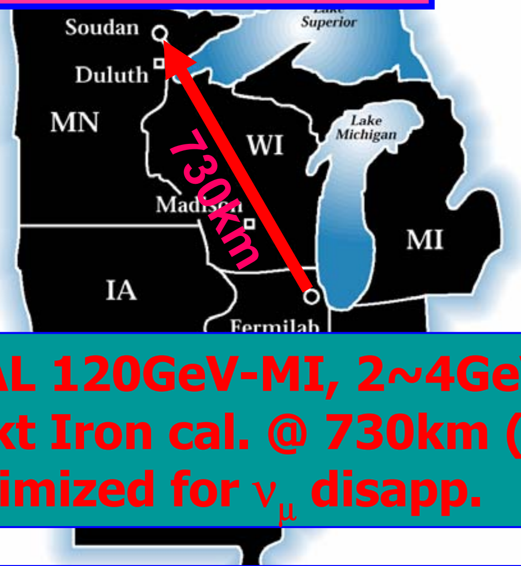


@$\sin^2 2\theta_{13}$=0.01

Smaller distance/lower energy → small matter effect
Pure CPV & Less sensitivity on sign of Δm^2
Combination of diff. E&L help to solve.

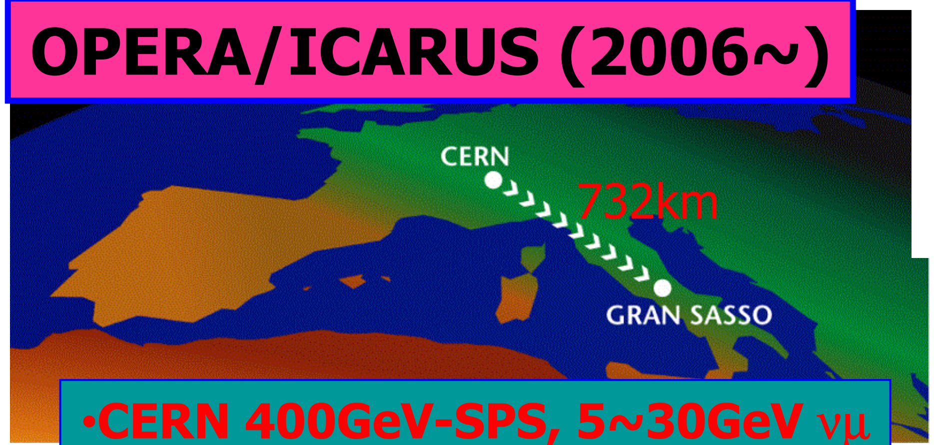
ν_e appeanrance in "present" experiments

MINOS (2005~)

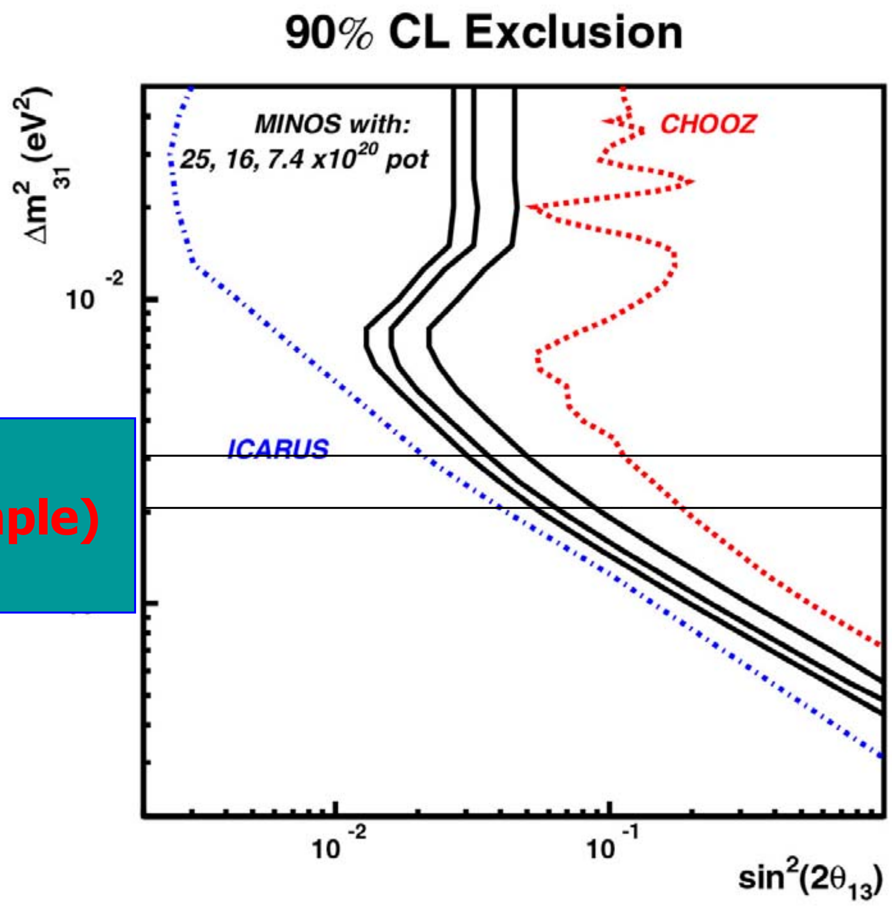


- FNAL 120GeV-MI, 2~4GeV $\nu\mu$
- 5.4kt Iron cal. @ 730km (1inch sample)
- Optimized for ν_μ disapp.

OPERA/ICARUS (2006~)



- CERN 400GeV-SPS, 5~30GeV $\nu\mu$
- Emulsion/Liq. Ar TPC @ 732km
- Optimized for ν_τ app.



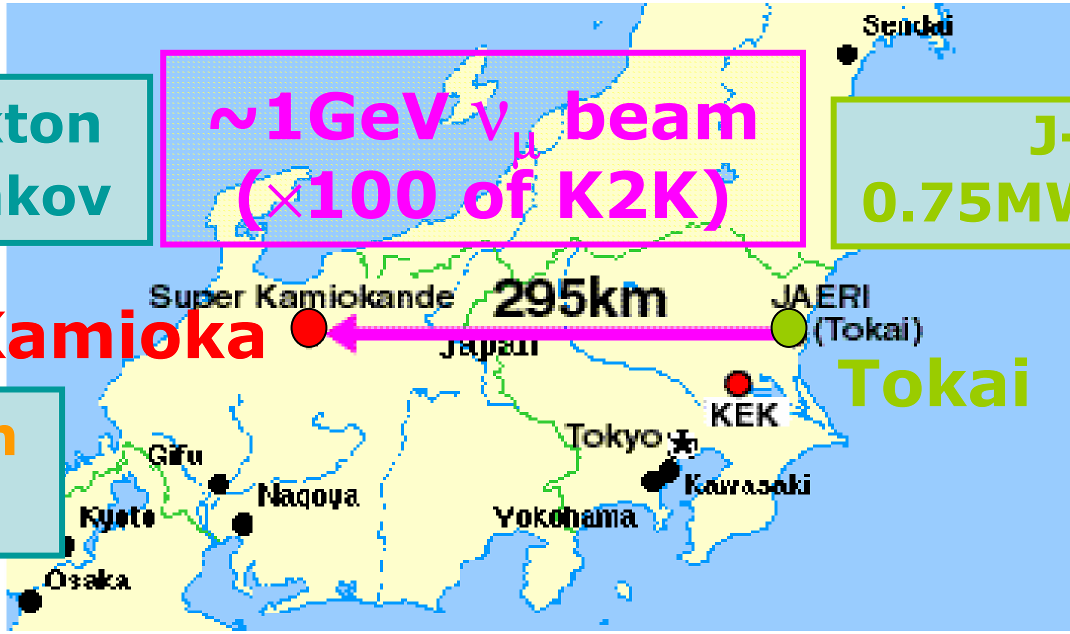
Not optimized for ν_e app.
Factor 2~3 improvement in sens.(90%)
→ Very small chance to "discover" (3σ)

T2K experiment (approved & start in 2009)

Long baseline neutrino oscillation experiment from Tokai to Kamioka.

Super-K: 50 kton Water Cherenkov

Phase2: Mton Hyper-K?



J-PARC 0.75MW 50GeV PS

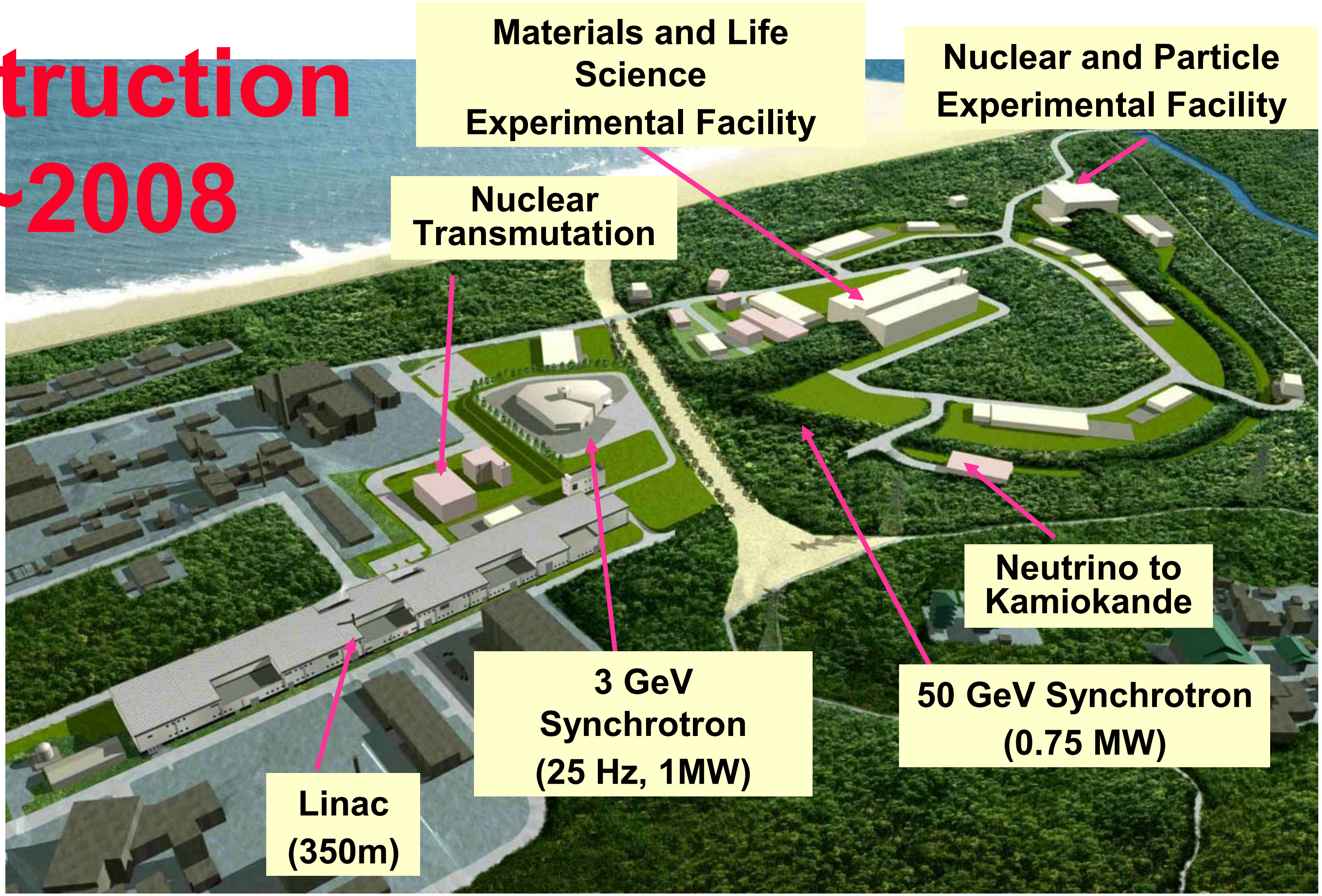
Phase2: 4 MW ?

Physics motivations

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

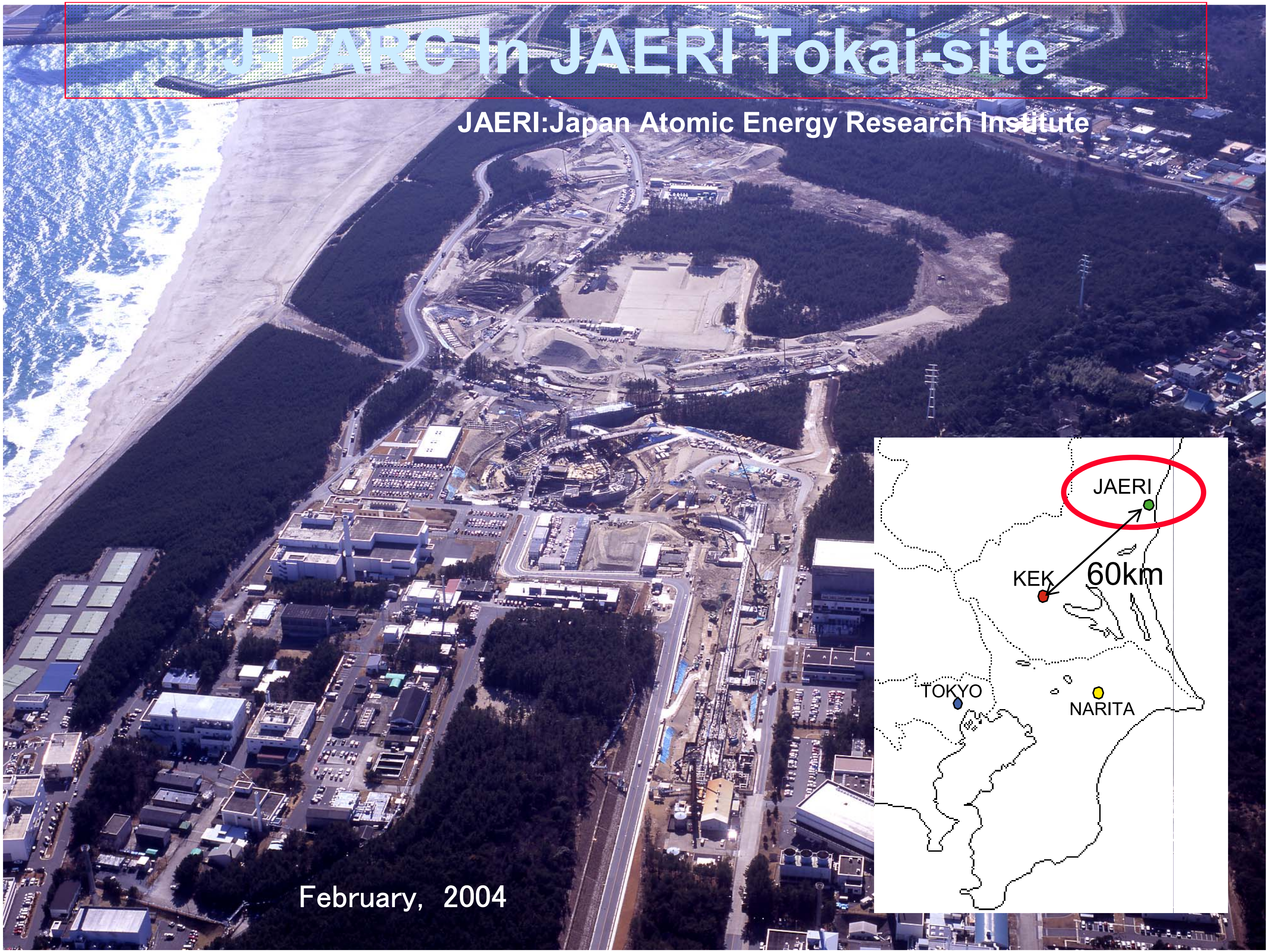
Japan Proton Accelerator Research Complex (J-PARC)

Construction 2001~2008



J-PARC in JAERI Tokai-site

JAERI:Japan Atomic Energy Research Institute



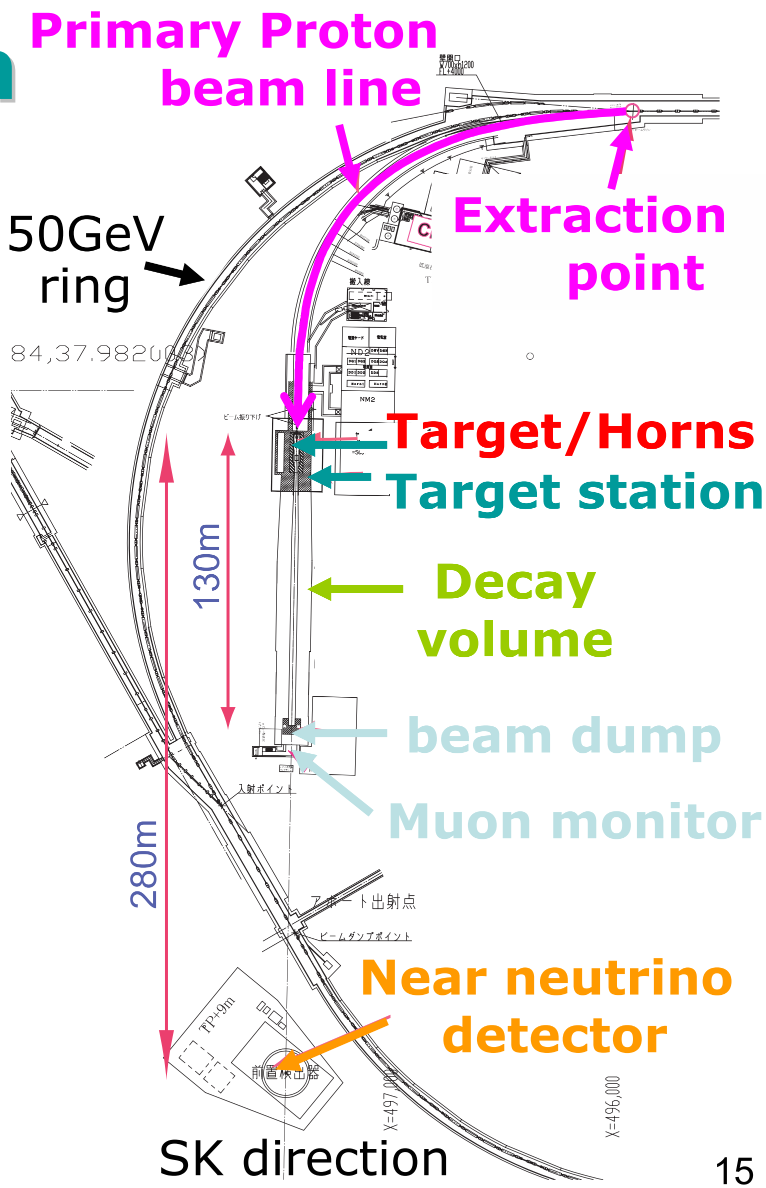
February, 2004

J-PARC Neutrino facility

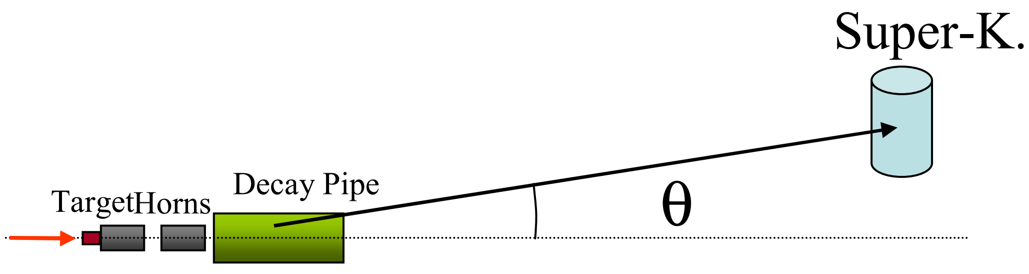
Approved in Dec. 2003 for 5 years construction (2004~2008JFY)

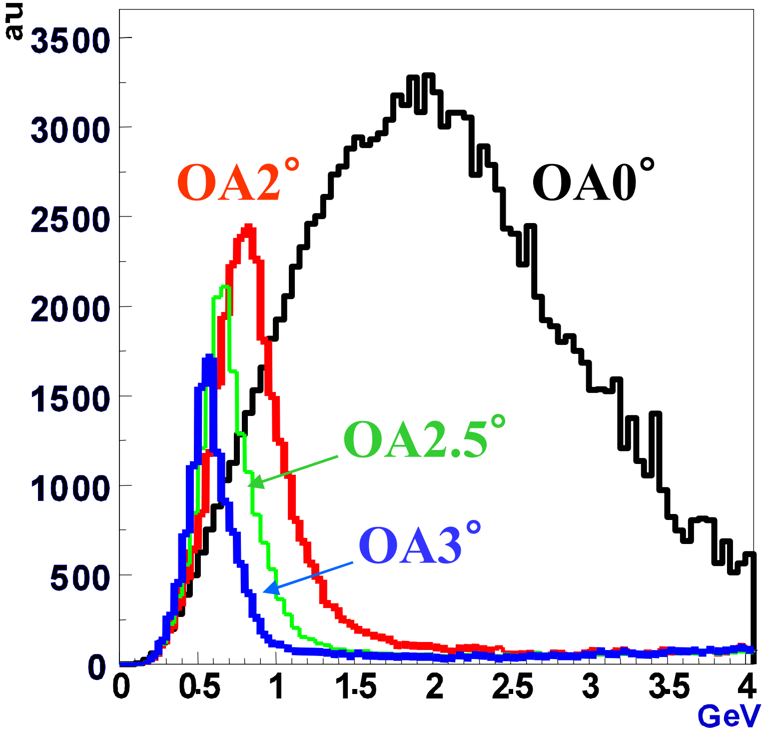
Components

- Primary proton beam line
  - Superconducting combined function
- Target/Horn system
- Decay volume (130m)
- Beam dump
- Muon monitor
- Near neutrino detector (280m)
- Second near neutrino detector (~2km): not approved yet

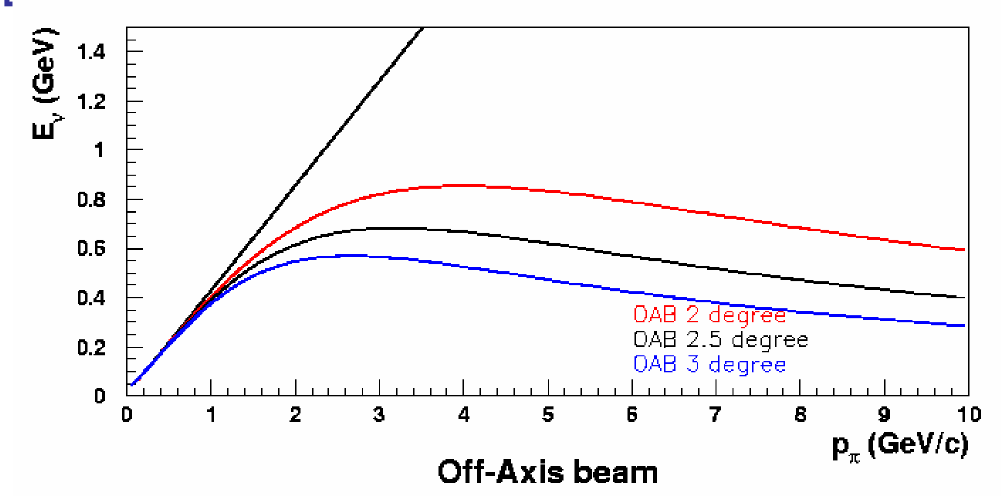


Off Axis Beam (Ref: BNL-E889 Proposal)





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

Ground breaking of ν facility @ J-PARC

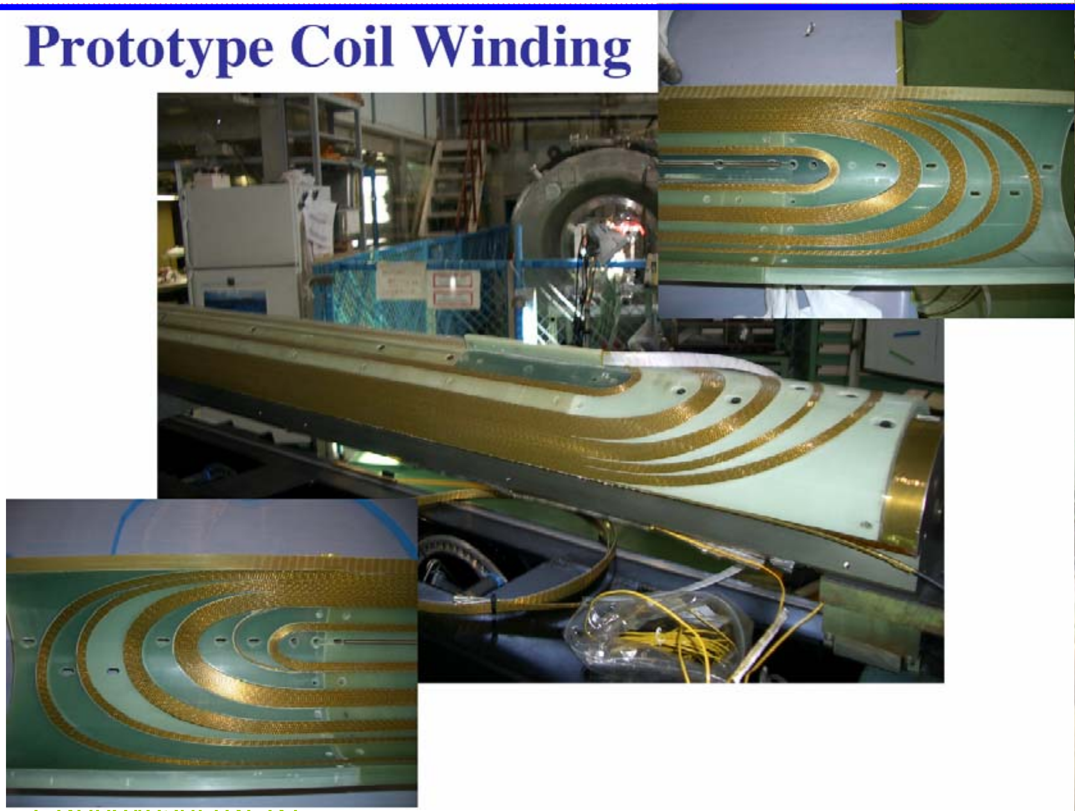
- Decay volume part
- July, 2004

R&D and construction of components

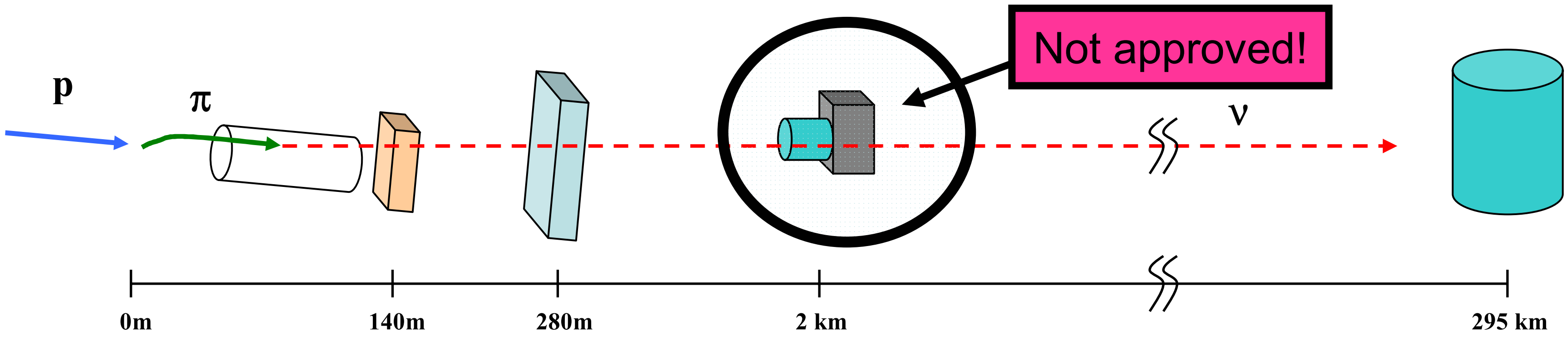
(1^{st}) Horn inner conductor prototype

Decay pipe

Superconducting combined function magnet

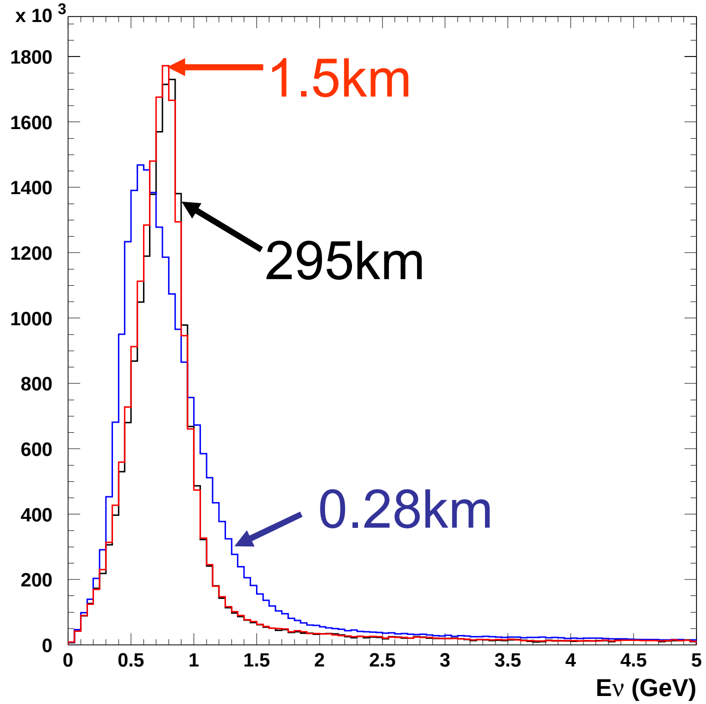


Detector complex

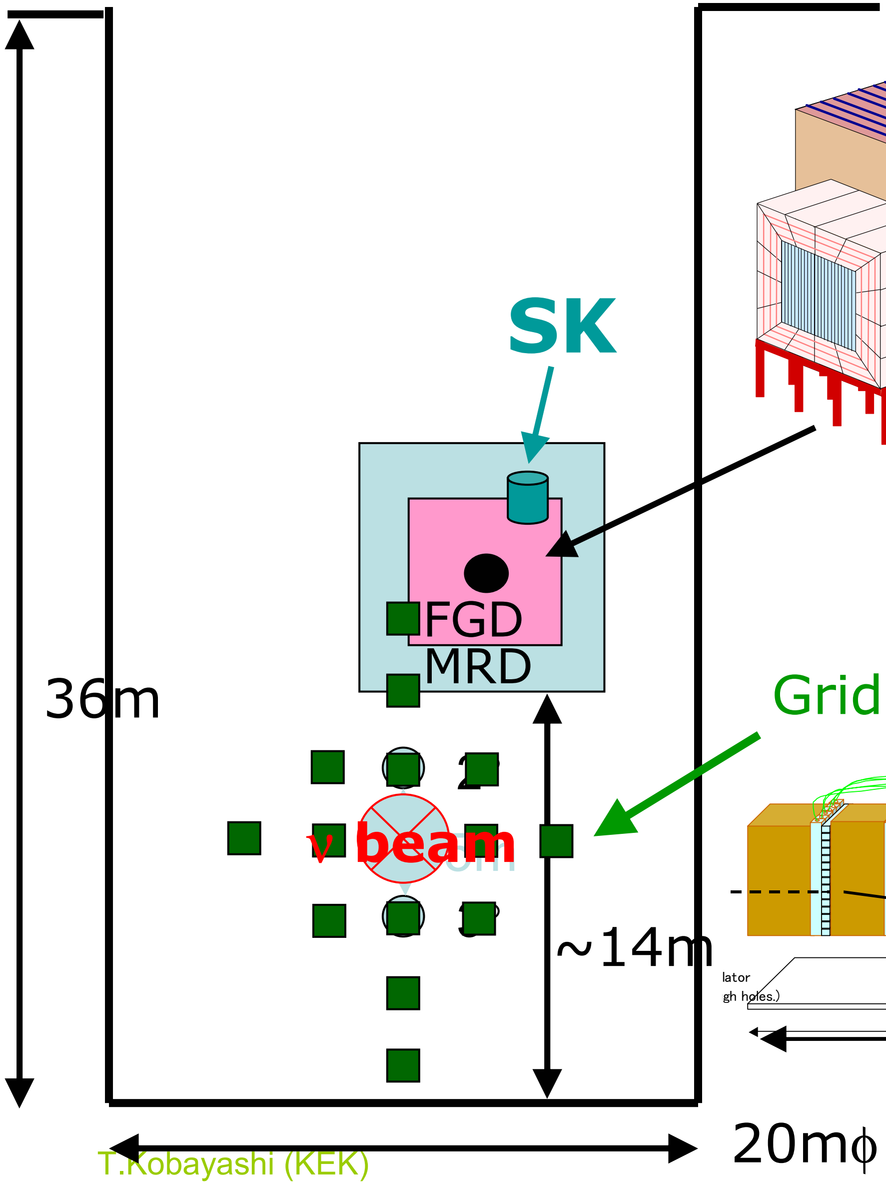


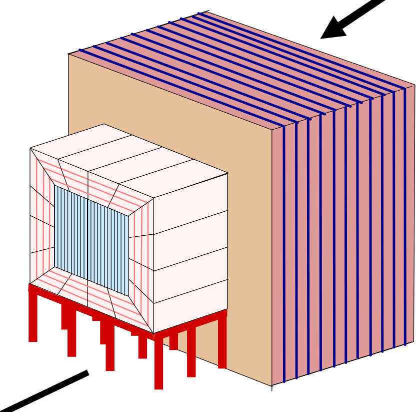
- **Muon monitors @ ~140m**
  - Fast (spill-by-spill) monitoring of beam direction/intensity
- **First Front detector @280m**
  - Intensity, Direction, Spectrum, ν interaction
- **Second Front Detector @ ~2km (not approved)**
- **Far detector @ 295km**
  - **Super-Kamiokande (50kt)**

Neutrino spectra at diff. dist

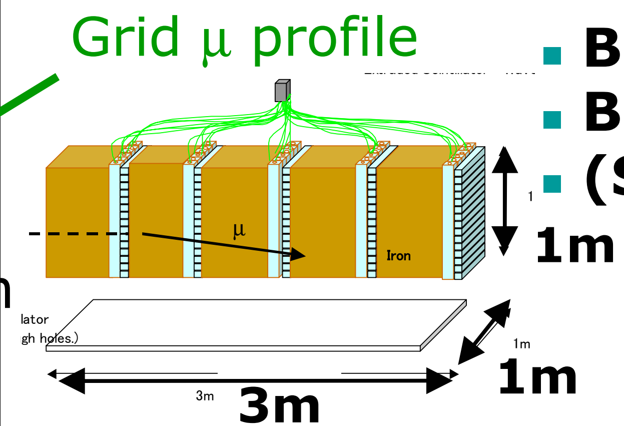


Near Detector @280m





- Off-axis (~2°)
- With Magnet
  - ν_μ and ν_e fluxes and spectra
  - ν interaction study (CC-QE,non-QE,π^0,)
  - Kaon contributions
- On-axis (0°)
  - Beam direction
  - Beam stability
  - (Spectrum)?



The detector design is just started.

θ_{13} measurement in T2K(-I)

(ν_e appearance search)

$P(\nu\mu\text{-}\nu e) =$

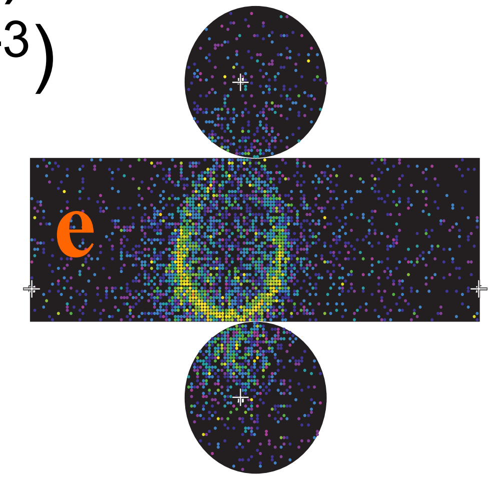
$\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\,\Delta m_{23}{}^2 L/E)$

$(@\Delta m^2=2\sim3\times10^{-3})$

signature:

CC QE event ($\nu_e+n\rightarrow p+e$)

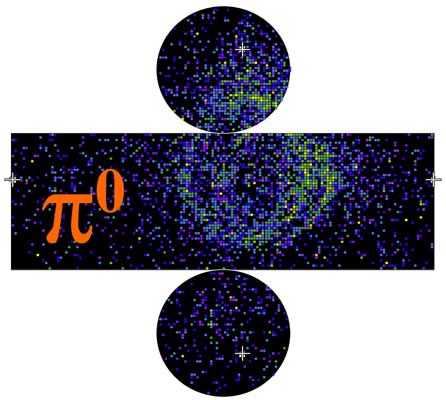
1ring e-like event



BG:

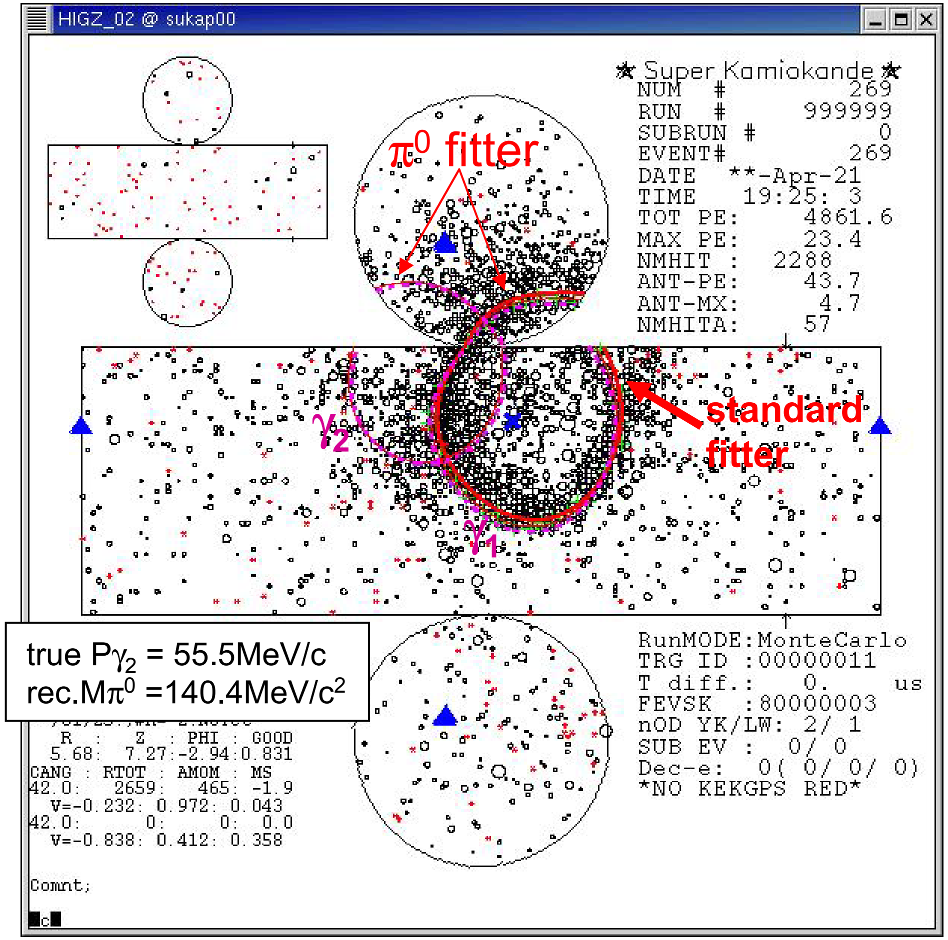
beam ν_e contamination (0.4% of $\nu\mu$)

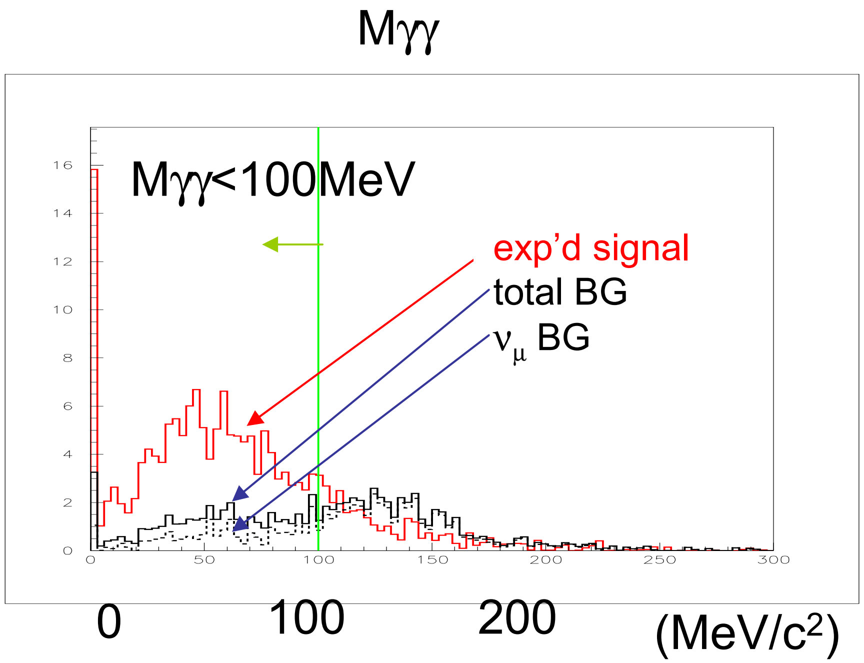
mis-reconstructed π^0 event in non-QE events ($\nu_e+X\rightarrow\nu_e(e)+\pi^0+X'$)



$\sin^2 2\theta_{23}=1$, $\delta=0$ are assumed.

π^0 rejection

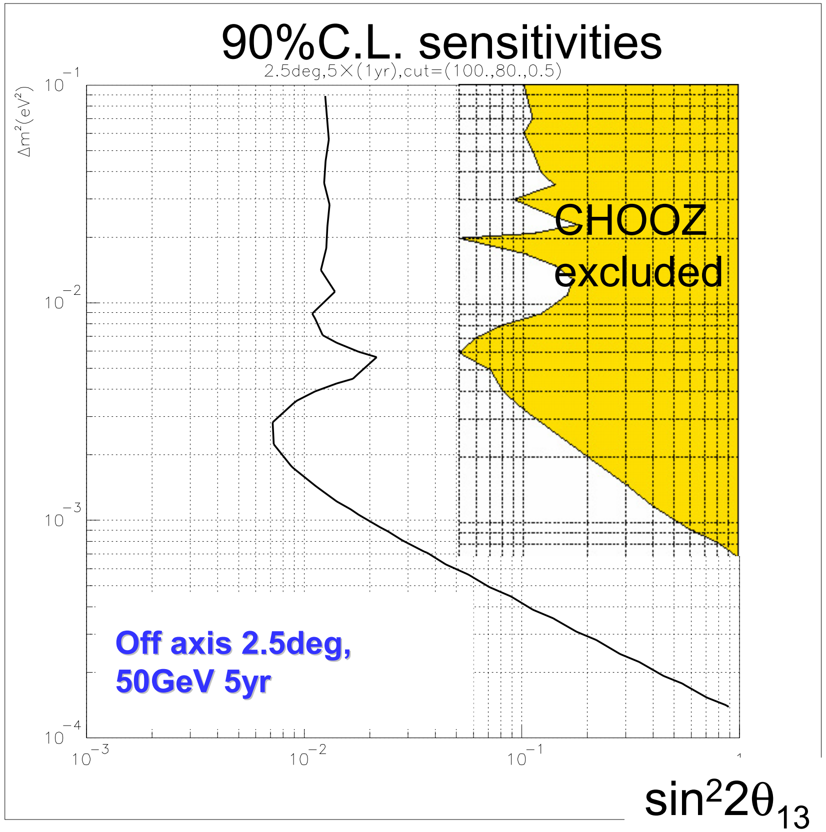


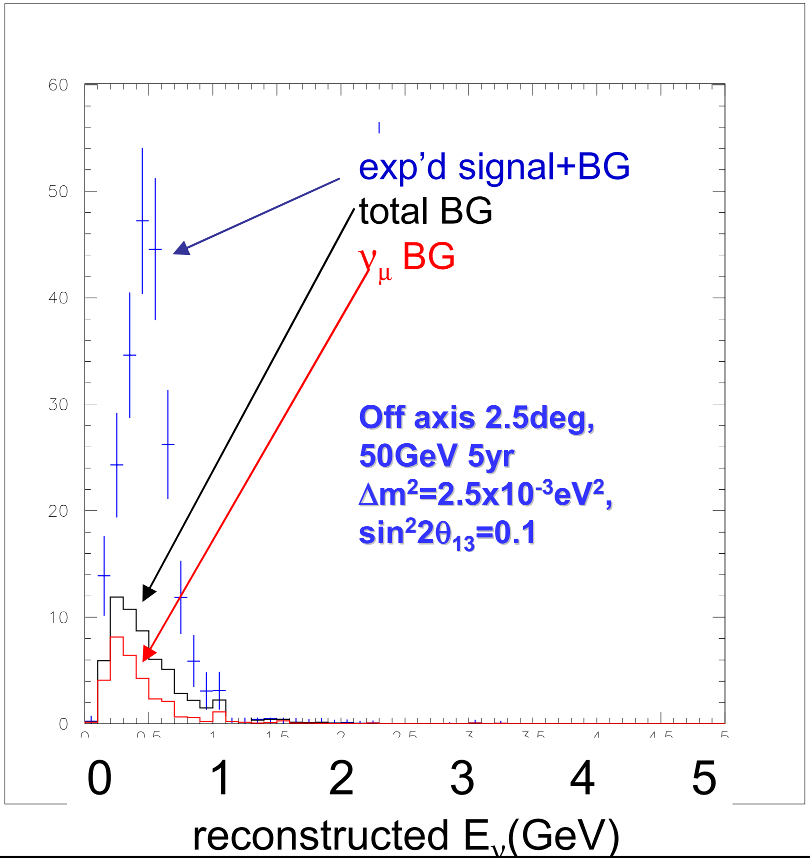


π0 events are still main BG.
For each 1ring e-like event, additional 1 ring is assumed and consistency with π^0 assumption is checked.

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	12	16	122	150
0.01	12	16	12	40

(OA 2.5deg, 50GeV 5yr)

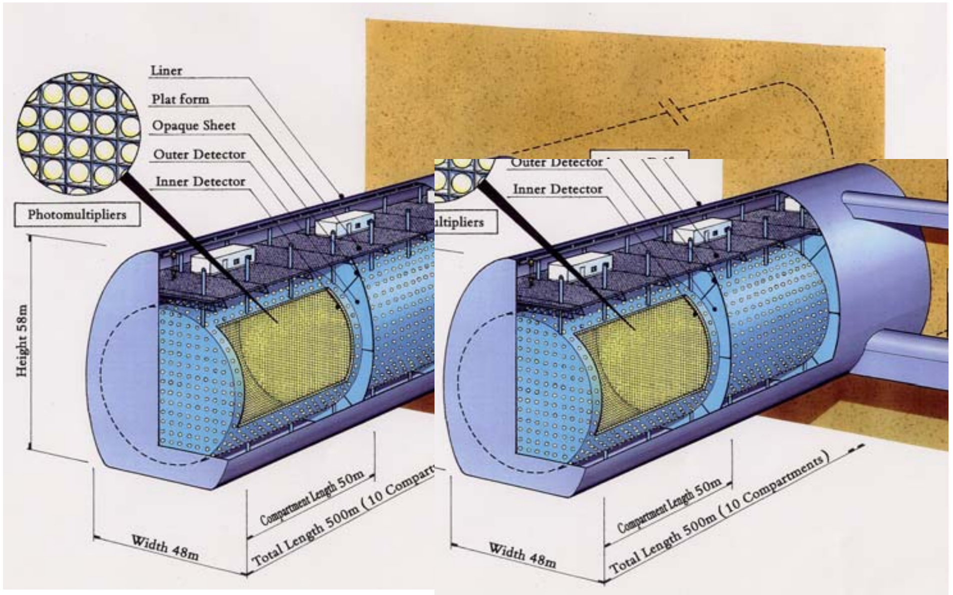
T2K 2nd phase for CPV: 4MW-PS & Hyper-K

0.75MW→4MW

- Rep. rate x 2.5
  - Double RF cavities (space OK)
  - Eliminate idling time in acc. cycle
- Double # of circulating protons
  - "barrier bucket method" to avoid space charge limit
- Issues
  - Achieve first goal (0.75MW)
  - Beam loss
  - Target,…

(these apply also for other projects)

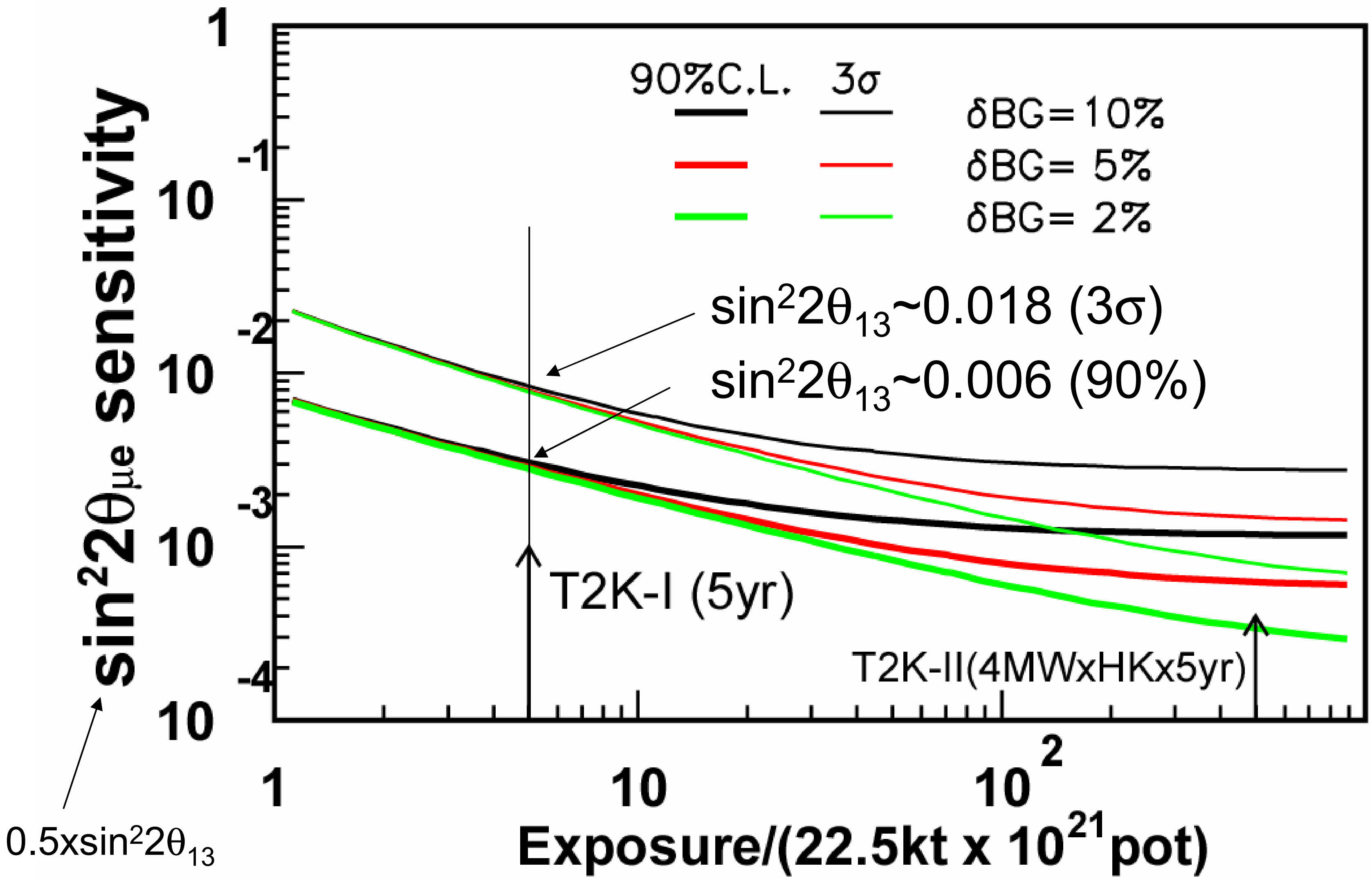
1Mt "Hyper-Kamiokande



2 detectors × 48m × 50m × 250m,
Total mass = 1 Mton

~T2K-I x 100 stat

Sensitivity for Mixing Angle



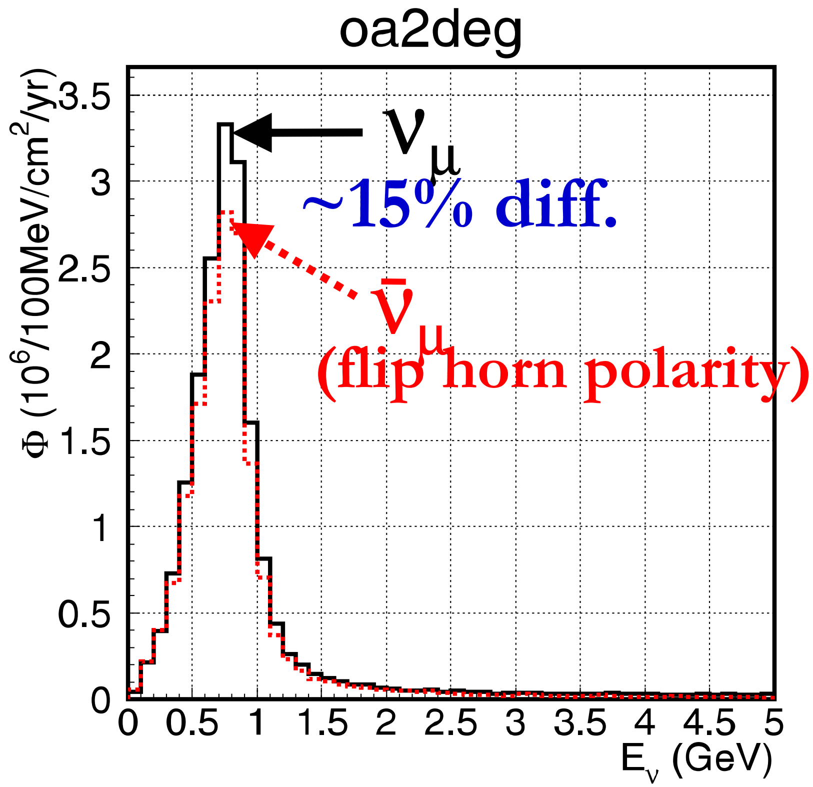
Background systematic error required to be ~ less than 10%

CPV measurements

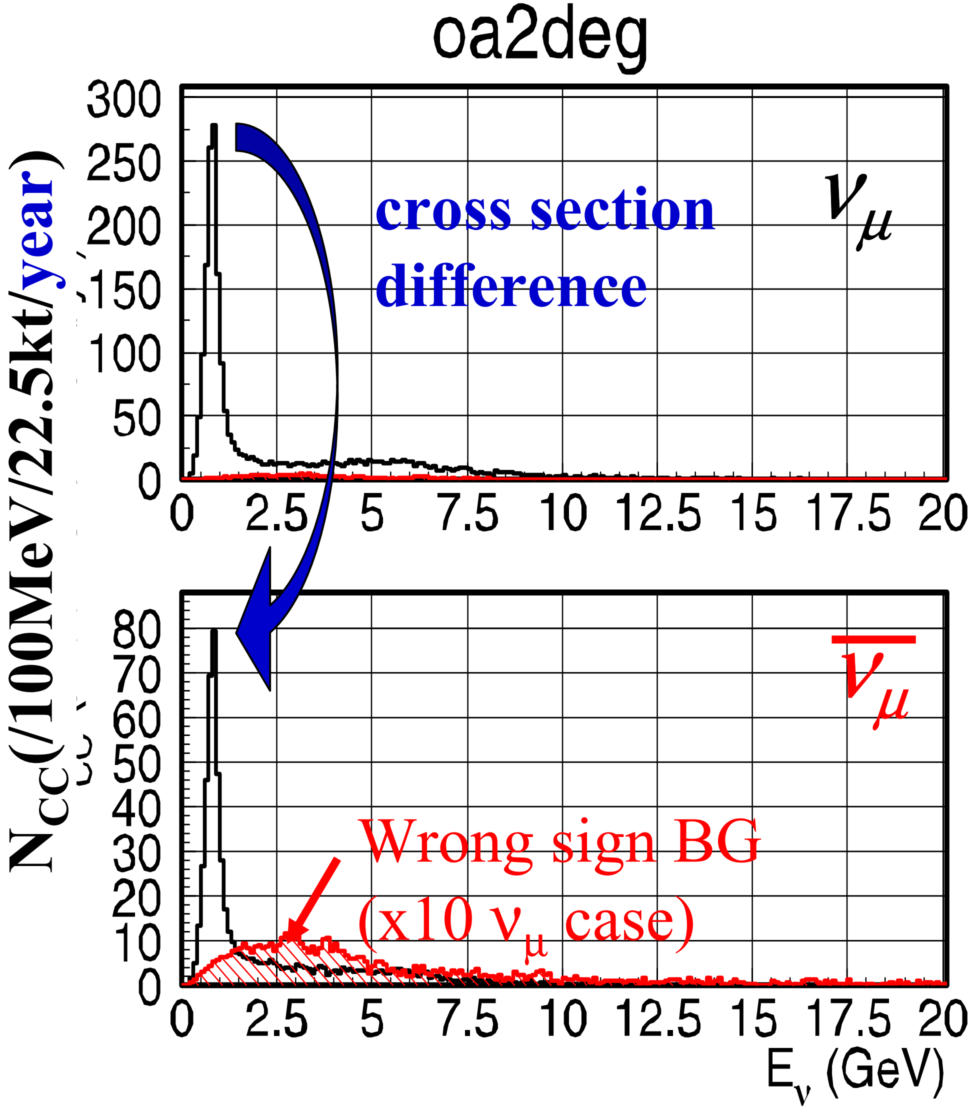
- Measure ν_e app. for both ν_μ and $\bar{\nu}_\mu$ beam
- Take asymmetry

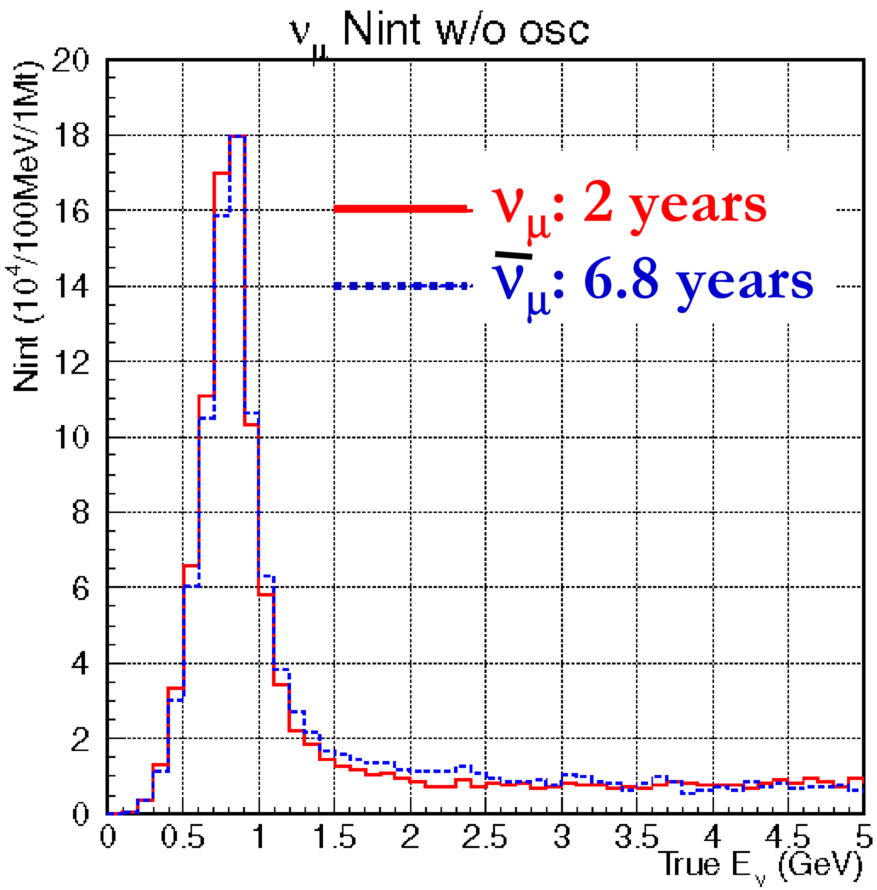
$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

ν_μ and $\bar{\nu}_\mu$ flux



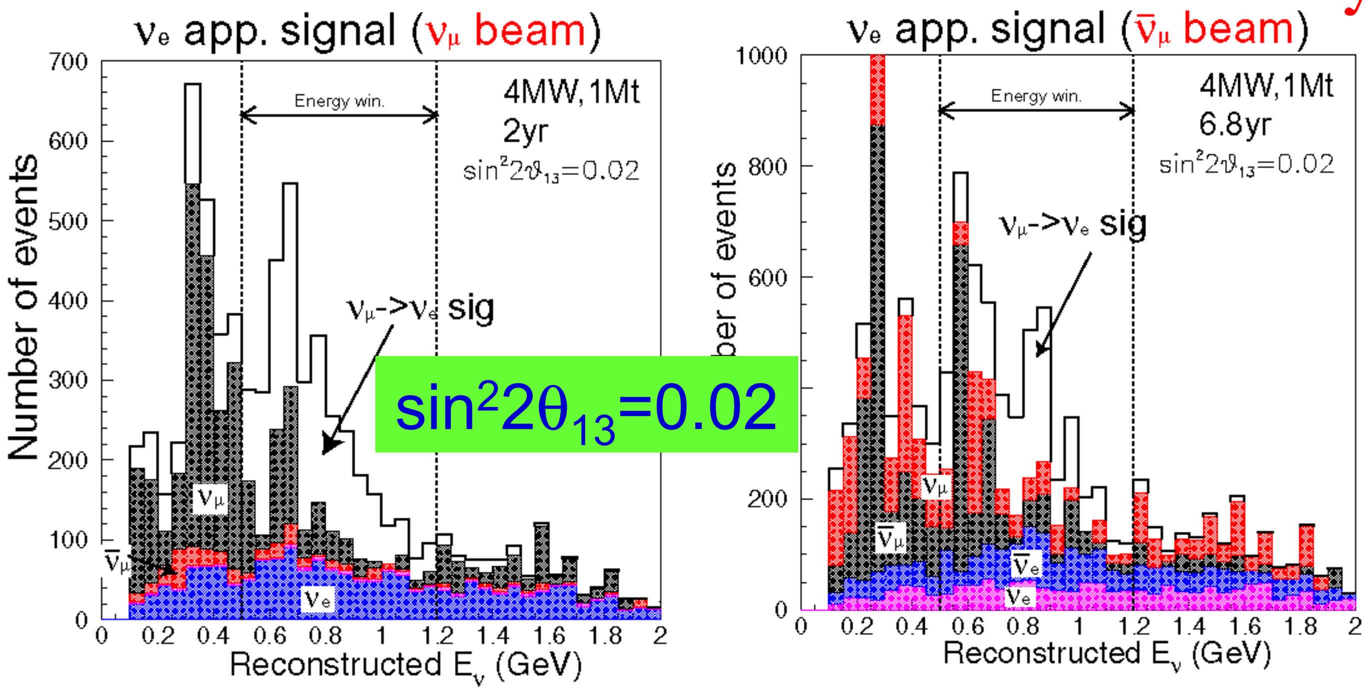
$\bar{\nu}$ / ν CC interaction spectrum for CPV meas.





Expected signal and BG (SK full sim)

Very Preliminary



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

ν_μ:2yr, ν_μ:6.8yr
4MW
0.54Mt

$\Delta m_{21}^2=6.9\times10^{-5}eV^2$
$\Delta m_{32}^2=2.8\times10^{-3}eV^2$
$\theta_{12}=0.594$
$\theta_{23}=\pi/4$
$\theta_{13}=0.05$ ($\sin^2 2\theta_{13}=0.01$)

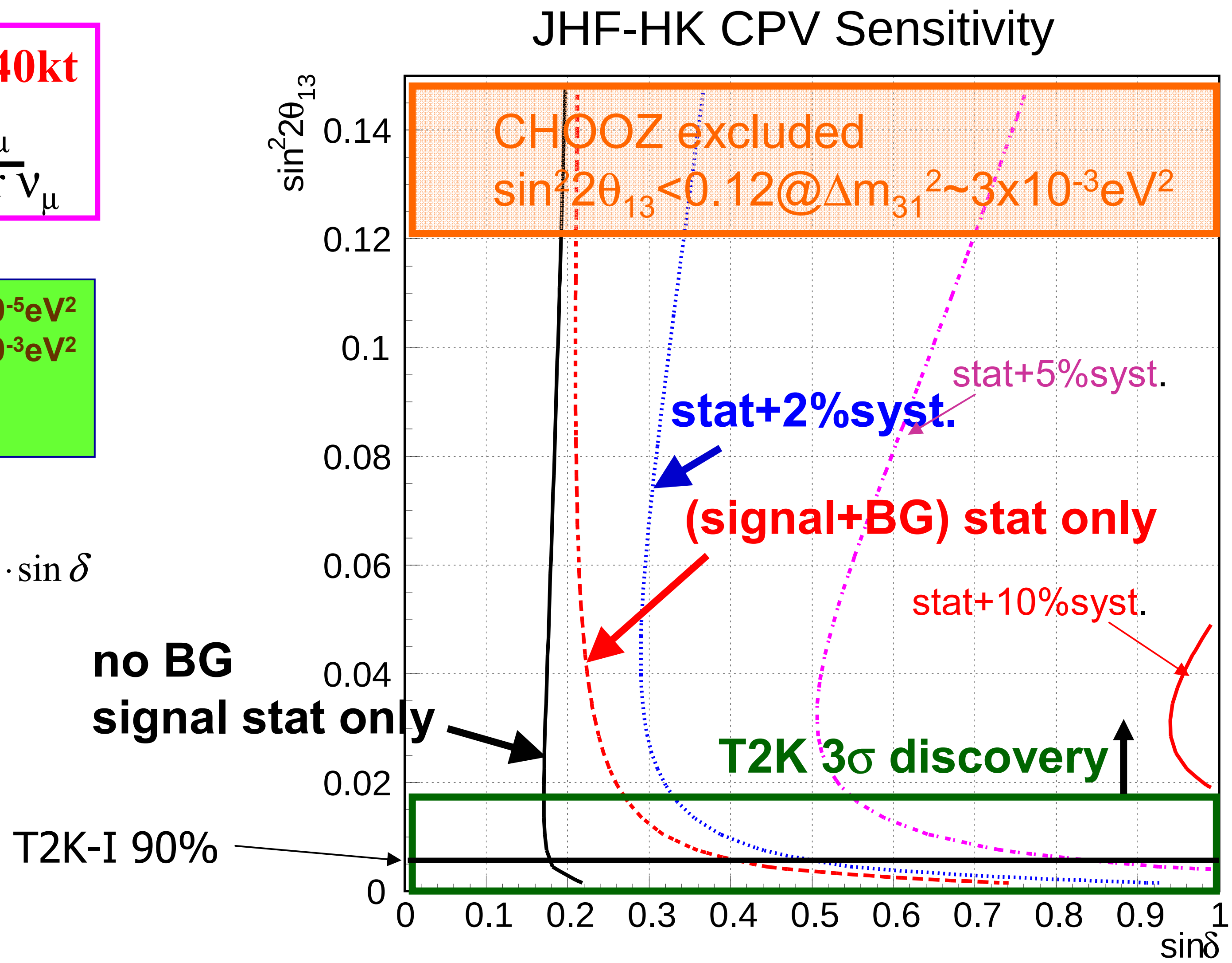
	signal		background				
	$\delta=0$	$\delta=\pi/2$	total	ν_μ	ν_μ	ν_e	ν_e
$\nu_\mu\rightarrow\nu_e$	536	229	913	370	66	450	26
$\bar\nu_\mu\rightarrow\bar\nu_e$	536	790	1782	399	657	297	430

3σ Sensitivity for CPV in T2K-II

4MW, 540kt
2yr for ν_μ
6~7yr for $\bar{\nu}_\mu$

Δm_{21}^2=6.9x10^{-5}eV^2
Δm_{32}^2=2.8x10^{-3}eV^2
θ_{12}=0.594
θ_{23}=π/4

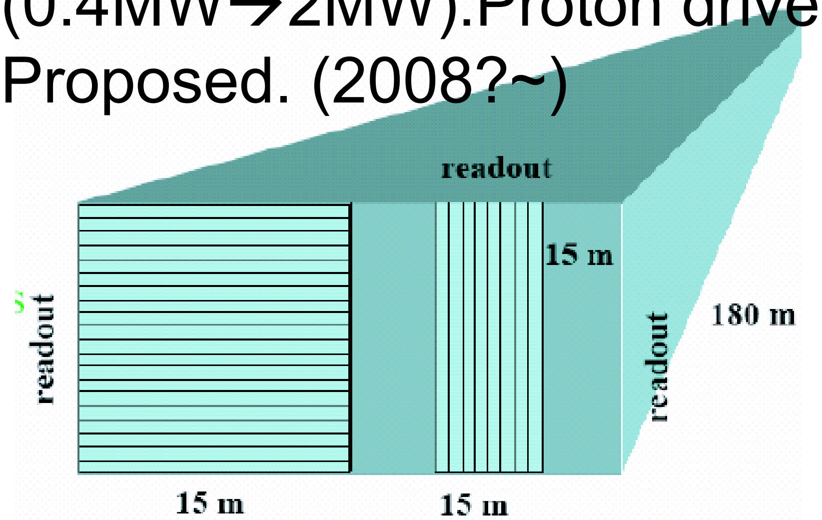
$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta$$

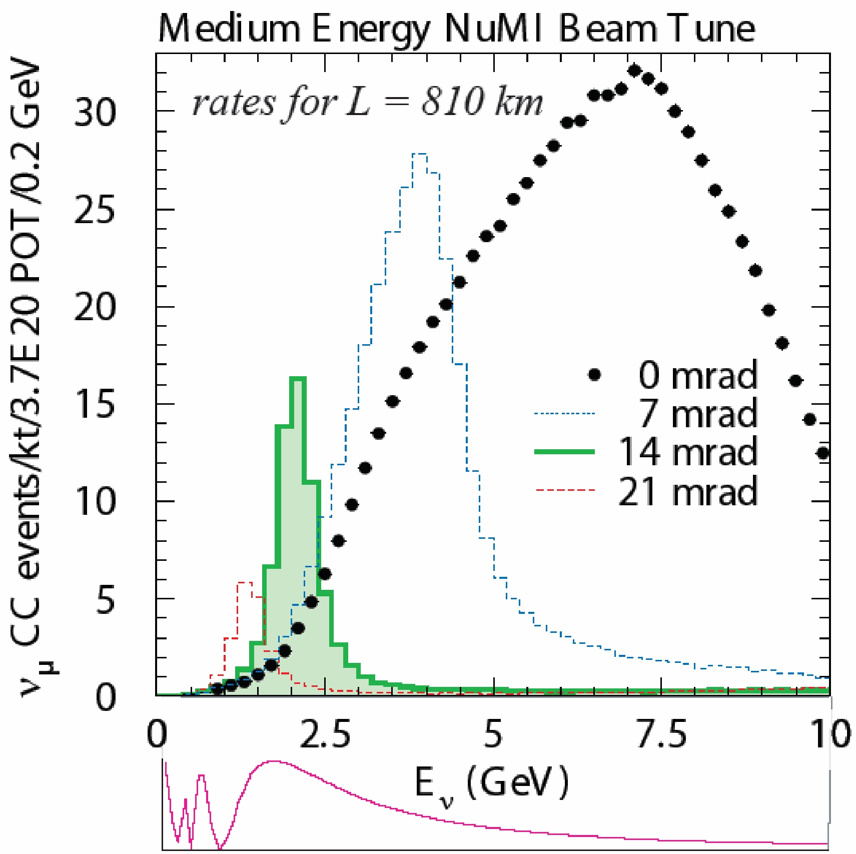


3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13}$>0.01 with 2% syst.

NOνA

- Use "existing" NuMI beamline (2005~) for MINOS
- New 50kt fine grained detector @~810km and @ 12km off axis
- Liq scint. tracker & particle board absorber (1/3X_0)
- 540k channel readout
- (Alternative:full active liq.sci.)
- Possible future upgrade of MI (0.4MW→2MW):Proton driver
- Proposed. (2008?~)



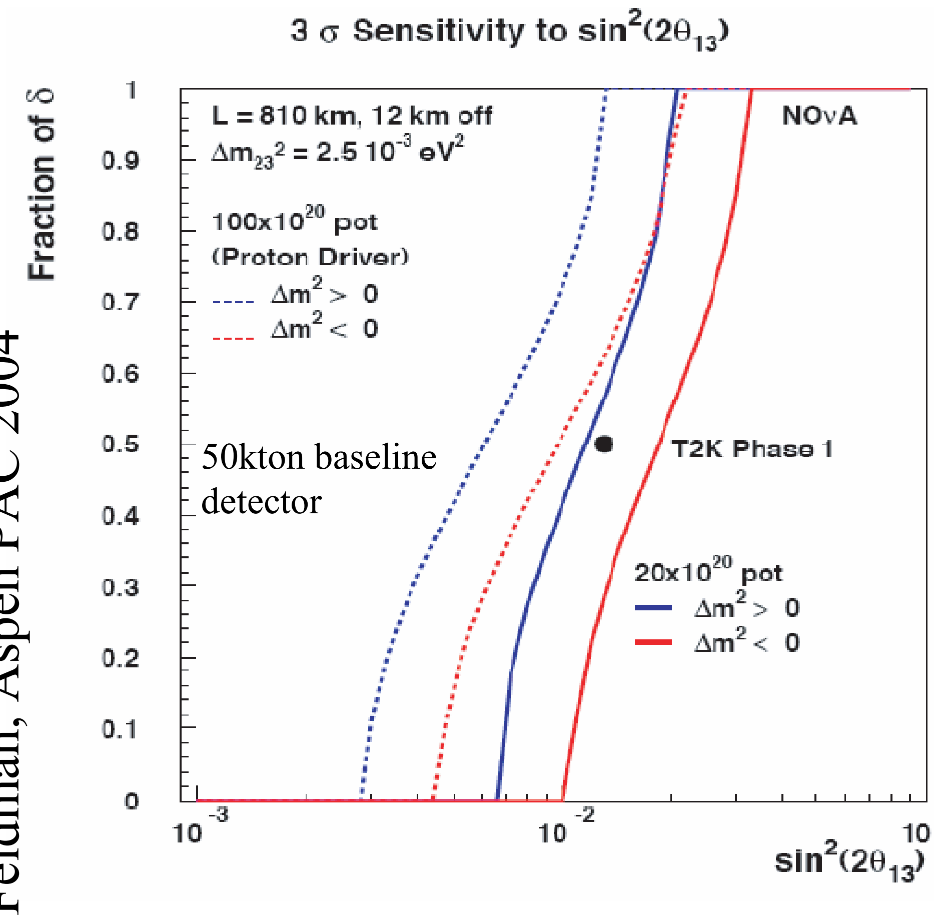


Assuming Δm^2=2.5x10^{-3}eV^2

Messier, ν2004

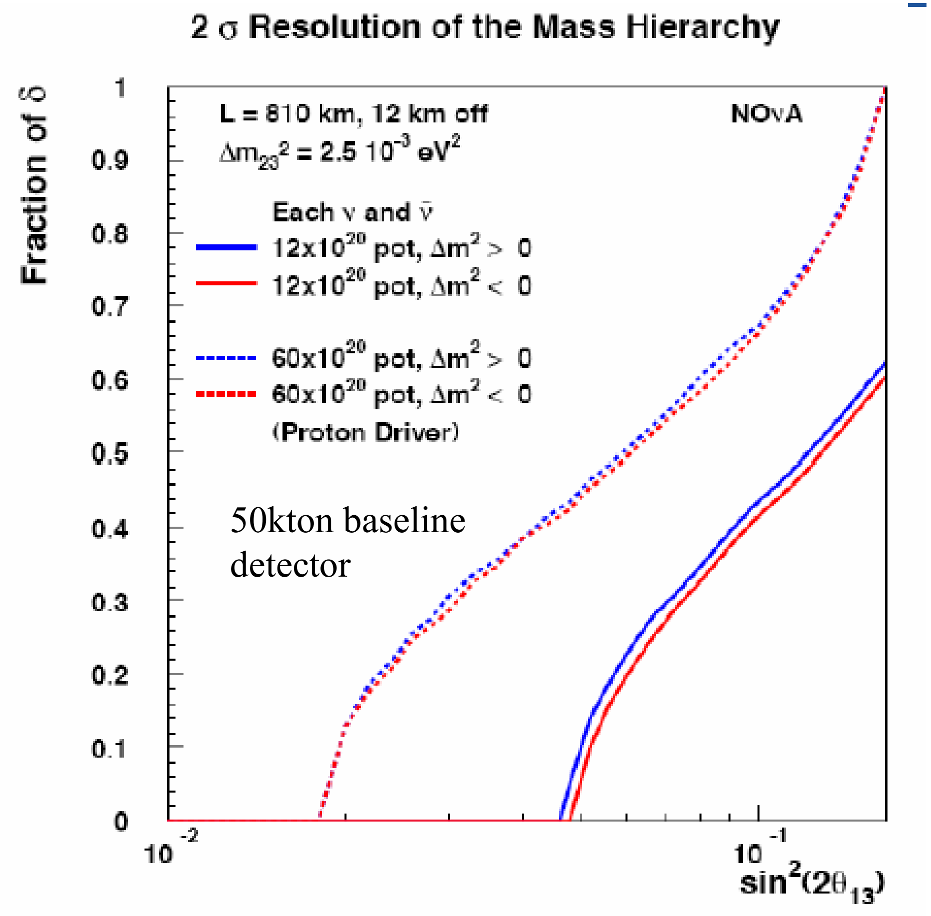
NOνA Physics Reach

ν_e appearance

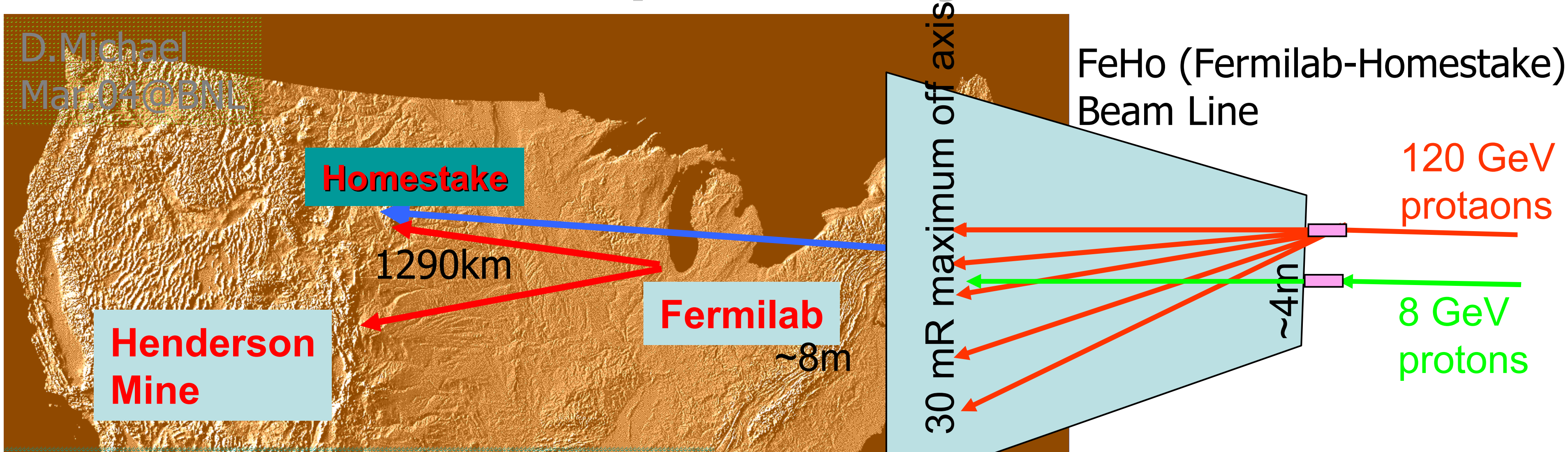


Feldman, Aspen PAC 2004

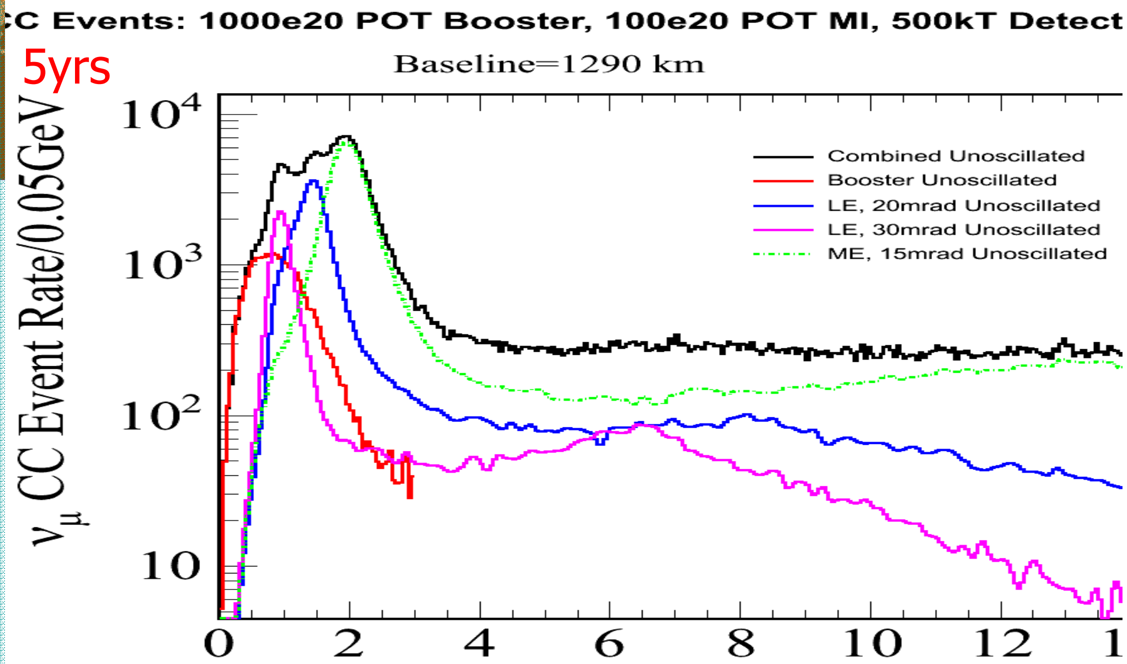
Mass hierarchy



Another possibility with PD

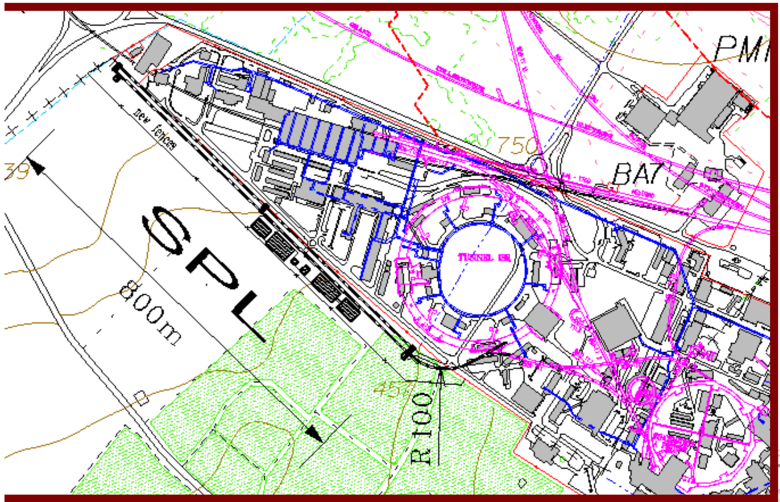


- A case study for future experiment with PD
- 2MW 8/120GeV PD→ "4MW"
- WB/OA to Homestake @1290km (or Henderson)
- Eν=0.5~3GeV
- Cover higher osc max
- 500kt WC or 100kt Liq.Ar
- ~50k νμ CC/year/500kt
- Studies of physics potential started

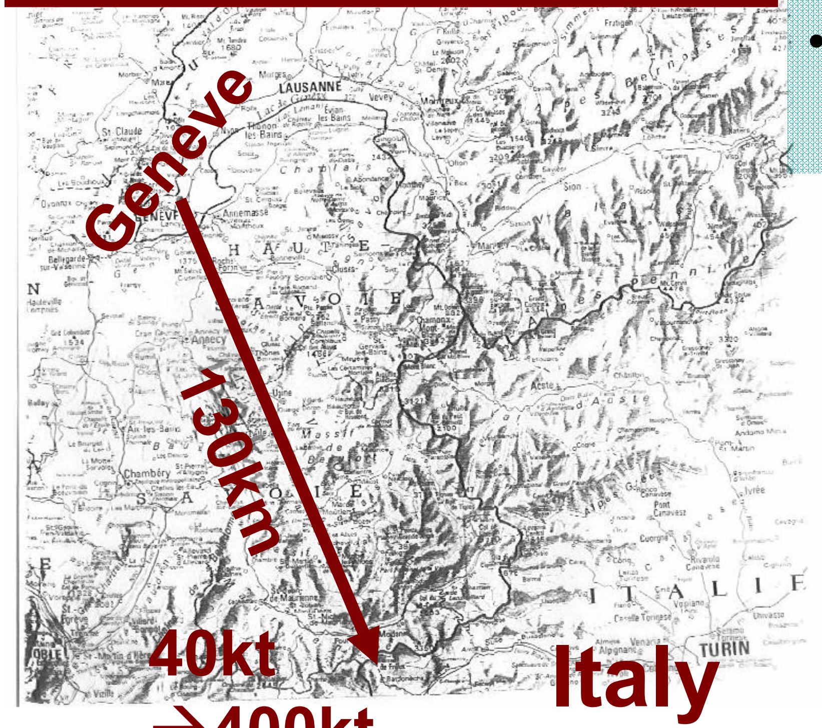


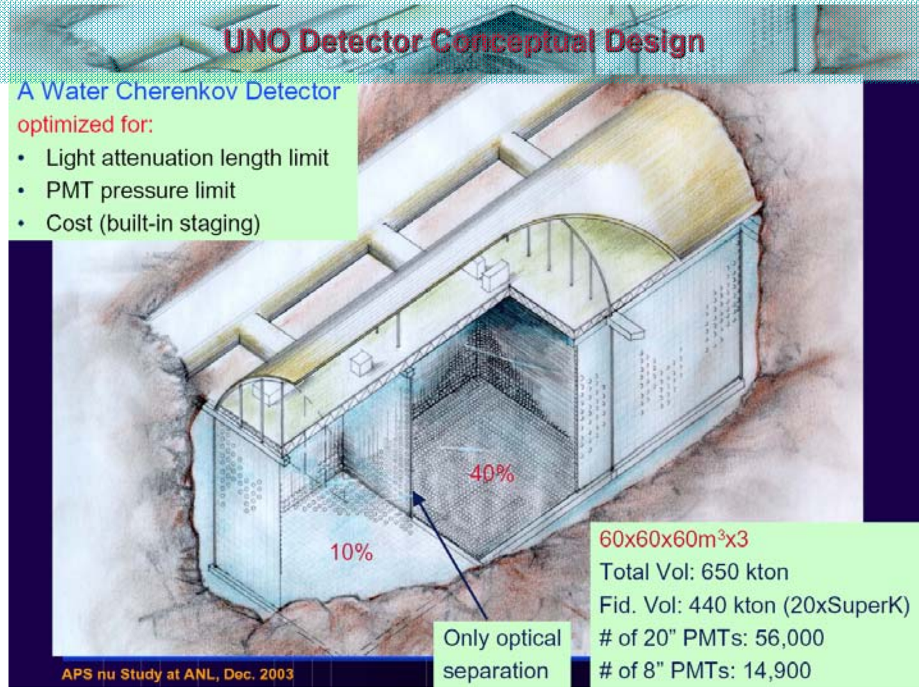
T.Kobayashi (KEK)

Europe: SPL→Frejus



- 4MW 2.2GeV Superconducting Proton Linac (SPL) @ CERN
- Low energy wide band (Eν~0.3GeV)
- L=130km
- Water Cherenkov 40→ 400kt (UNO)
- ~18,000 νμ CC/year/400kt
  θ_{13}, CPV
- Small matter effect
- SPL in R&D, UNO in conceptual design





(Ref: Diwan et al., PRD68, 012002, 2003)

BNL-Homestake

- 28GeV AGS upgrade to 1MW (2MW) cf current 0.1MW
- Wide band beam (0.5~6GeV)
- L=2,540km
- Mton detector
- ~13,000 ν_μ CC/year/500kt
- **Cover higher osc. maxima**

Goals

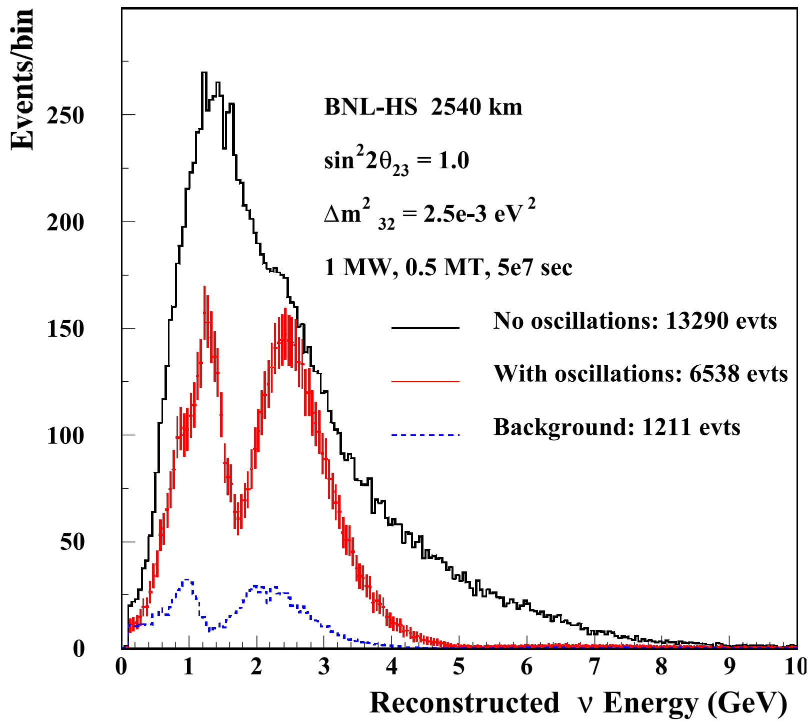
ν_e appearance

- Sign of Δm_{23}
- CPV

θ_{12}, Δm_{12}

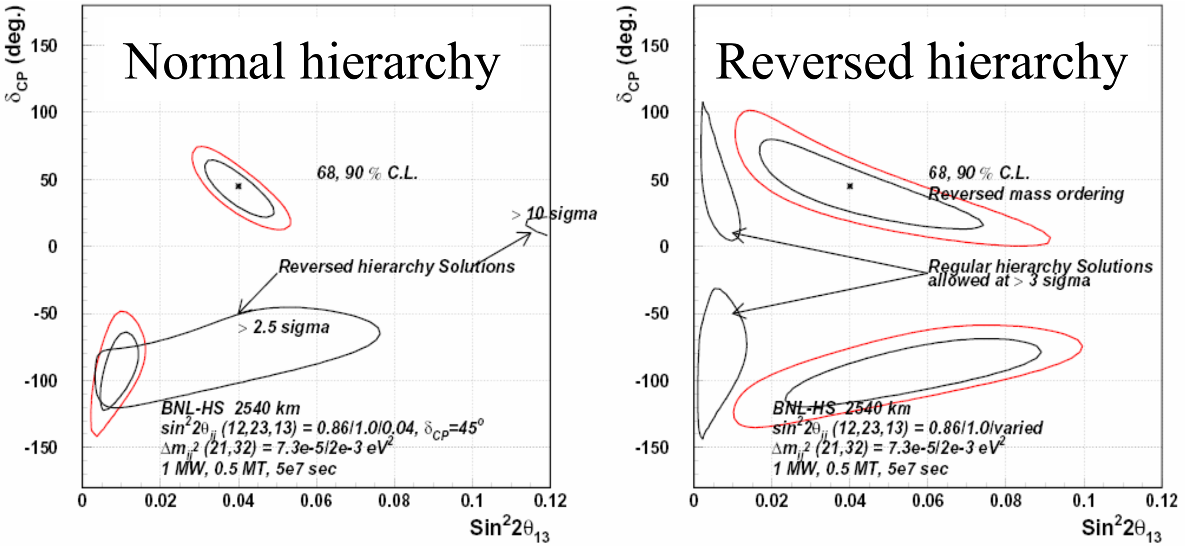
Possible w/ only ν run at certain parameter region

- LOI written.

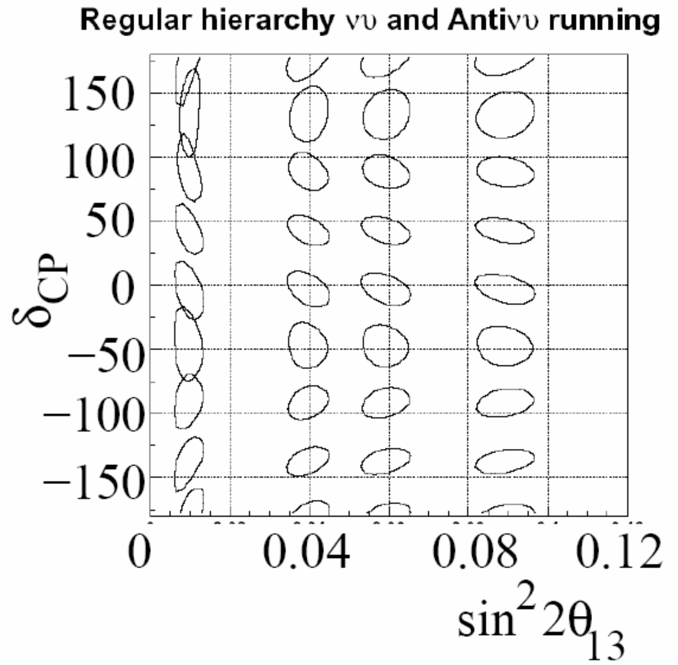


Brookhaven to Homestake Physics Reach

Even with only ν data,
CP violation and mass hierarchy are visible
in some regions of parameter space.



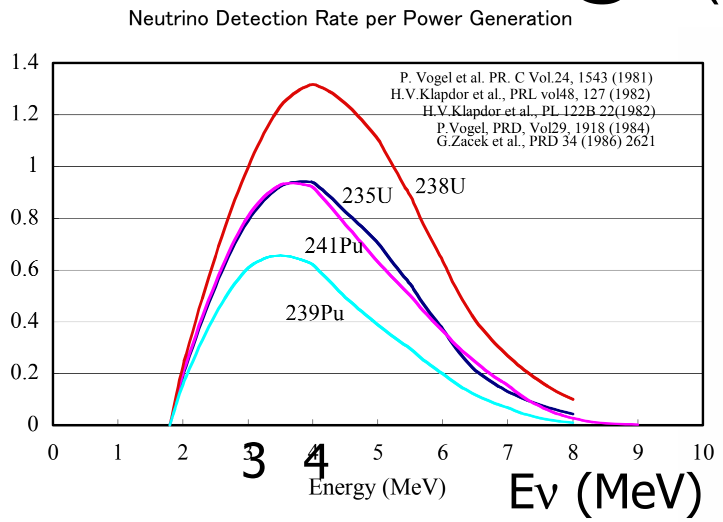
Diwan, 3/2004 APS study meeting

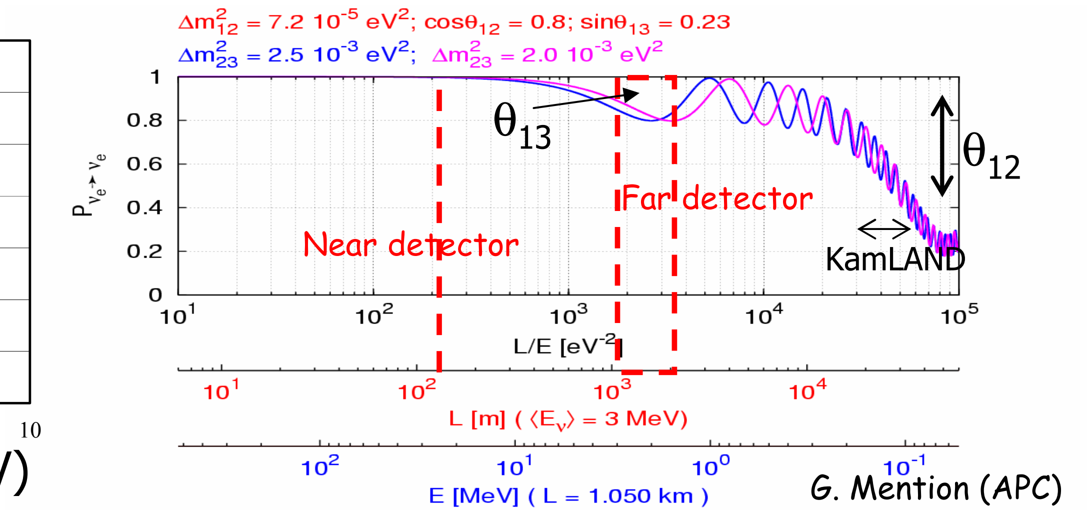


But with both ν and $\bar{\nu}$ running, CP precision much higher

Reactor $\bar{\nu}_e$ disappearance

- $\bar{\nu}_e$ from nuclear reactor <E>~3MeV
- $1-P(\nu_e \to \nu_e) = \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31}L/4E) + O(\Delta m^2_{21}/\Delta m^2_{31})$: pure θ_{13}
- Small systematic error (<1%) required
- Identical near det @ O(100)m & far det @a few km



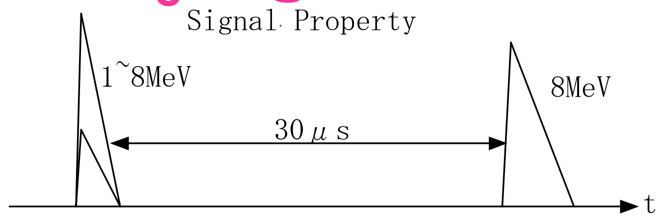


$$\bar{\nu}_e + p \to n + e^+$$

$$e^+ + e^- \to 2\gamma \quad (E_\nu - 0.8\ MeV)$$

$$n + Gd \to Gd' + \gamma s \left(\sum E = 8\ MeV\right)$$

$\bar{\nu}_e$ signature



T.Kobayashi (KEK)

Complementarity of Reactor-Accelerator Meas.

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

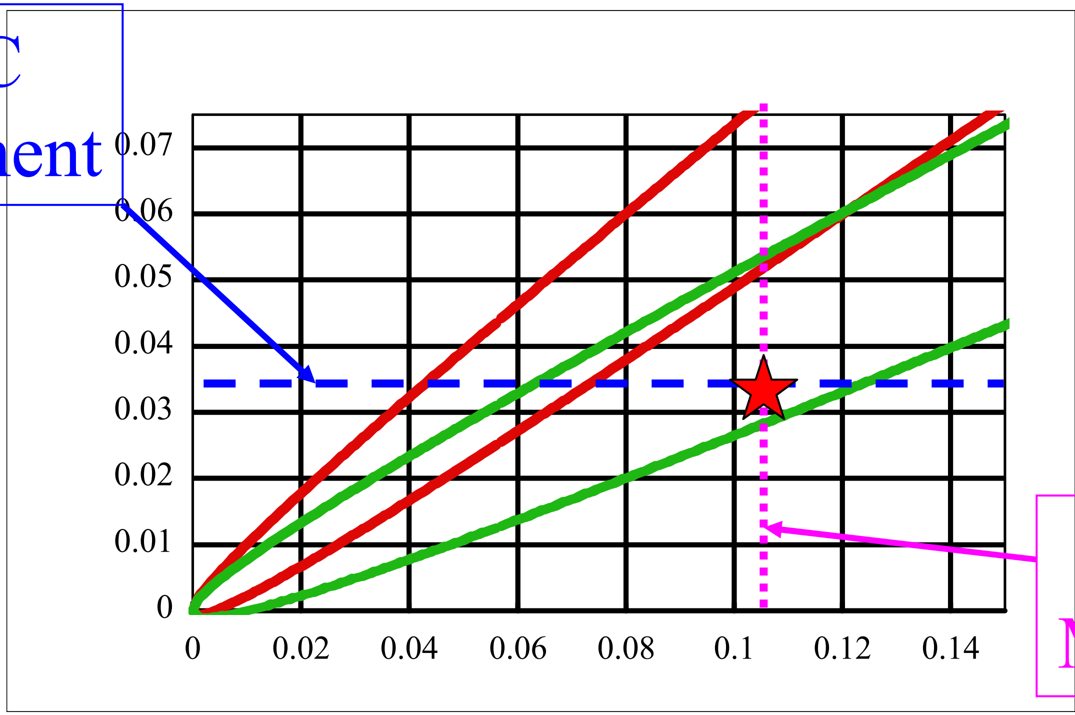
Reactor-Accelerator combination
=> a lot of physics potential

* Answer to θ_{23} degeneracy

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

J-PARC Measurement

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

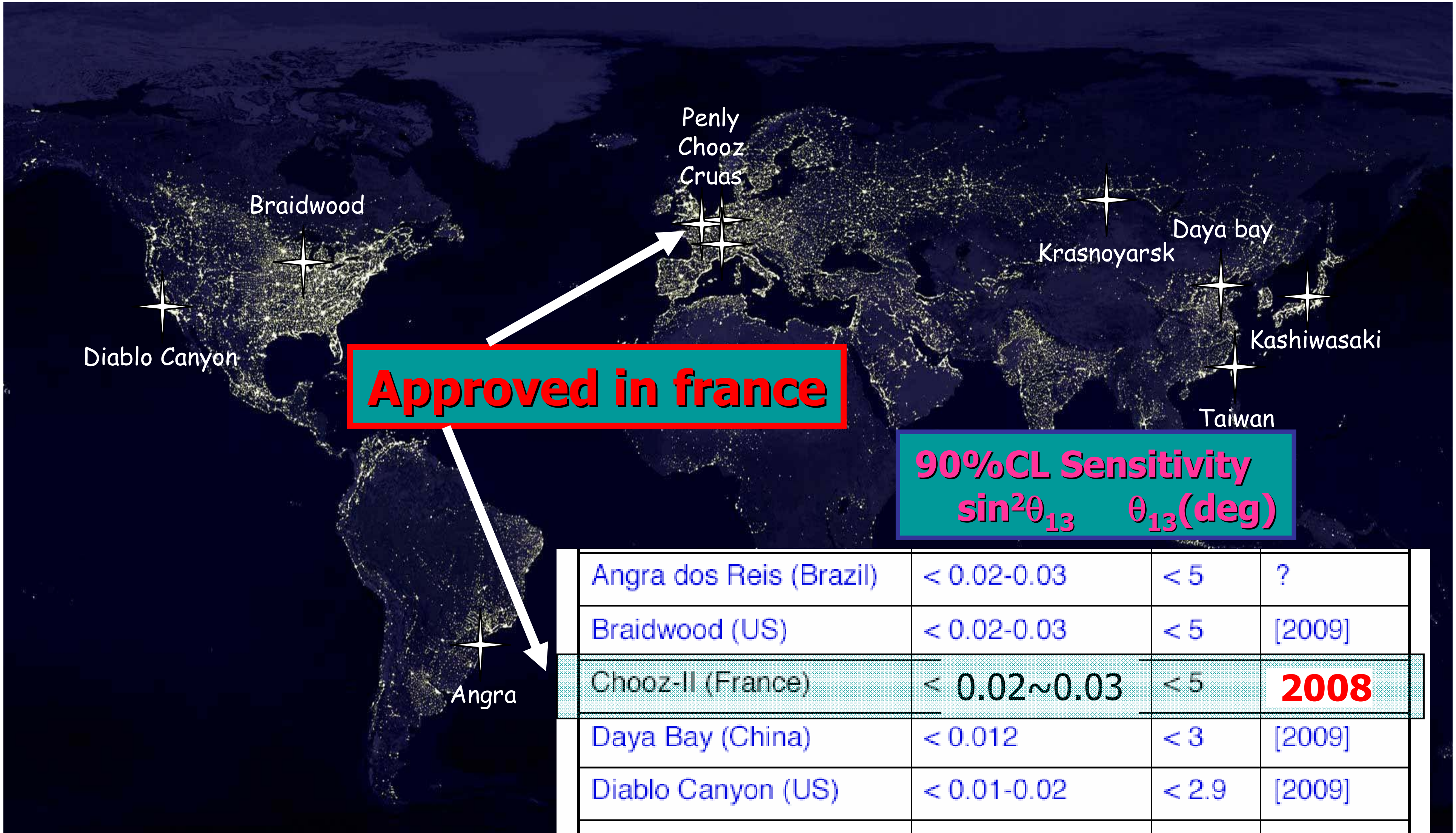


$\sin^2 2\theta_{13}$

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

Reactor Measurement

Reactor Experiment Proposals

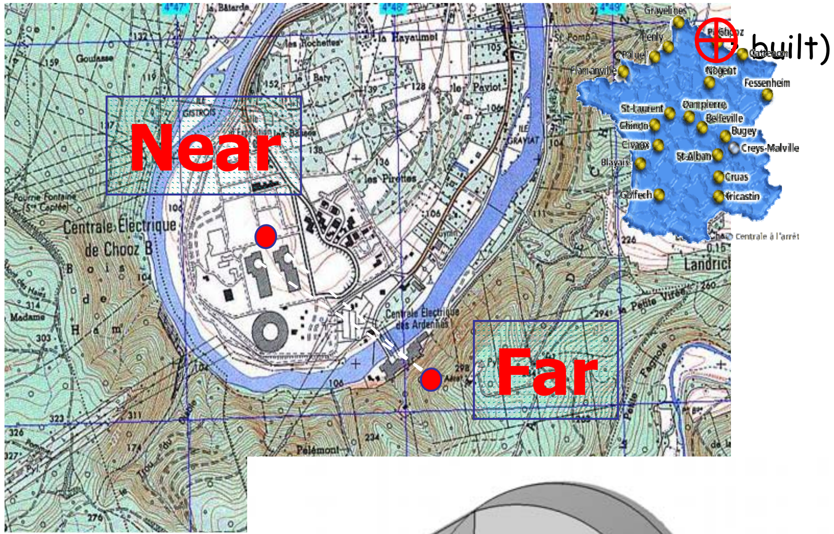


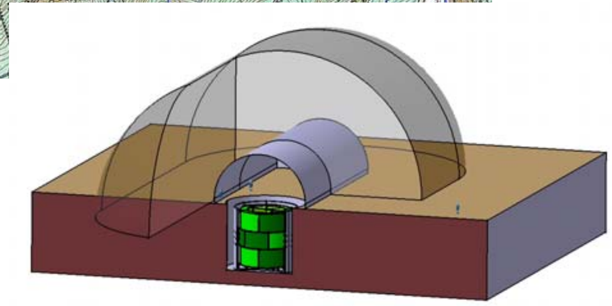
Approved in france

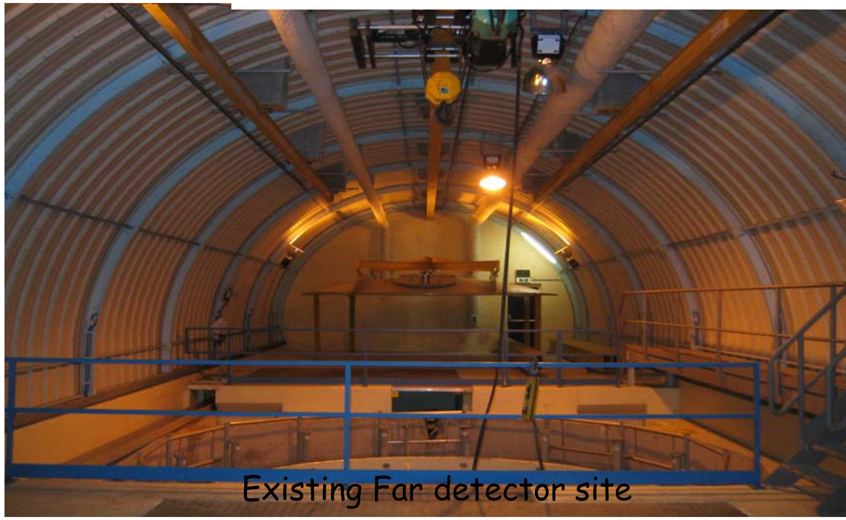
	90%CL Sensitivity sin$^2\theta_{13}$	θ_{13}(deg)	
Angra dos Reis (Brazil)	< 0.02-0.03	< 5	?
Braidwood (US)	< 0.02-0.03	< 5	[2009]
Chooz-II (France)	< 0.02~0.03	< 5	**2008**
Daya Bay (China)	< 0.012	< 3	[2009]
Diablo Canyon (US)	< 0.01-0.02	< 2.9	[2009]
Krasnoyarsk (Russia)	< 0.016	< 3.6	?
Kashiwazaki (Japan)	< 0.026	< 4.6	[2008]

Double-CHOOZ

- Twin reactor cores
  - P=2x4.2 GWth
- Two 10 tons detectors
  - 80% dodecane + 20% PXE + 0.1% Gd
  - Near: 100-200 m – 60-80 mwe
  - Far: 1.05 km - 300 mwe
- 3 years Sensitivity
  - **0.6%** systematics
  - **No signal: $\sin^2(2\theta_{13})$ < 0.02-03 (90% C.L.)**
  - Signal: $\sin^2(2\theta_{13}) > 0.04\text{-}05\ (3\sigma)$
- Prospect (**approved & funded in France**)
  - 2007: far detector running
  - **2008: near detector running**
  - Cost ~7Meuros + civil constr.

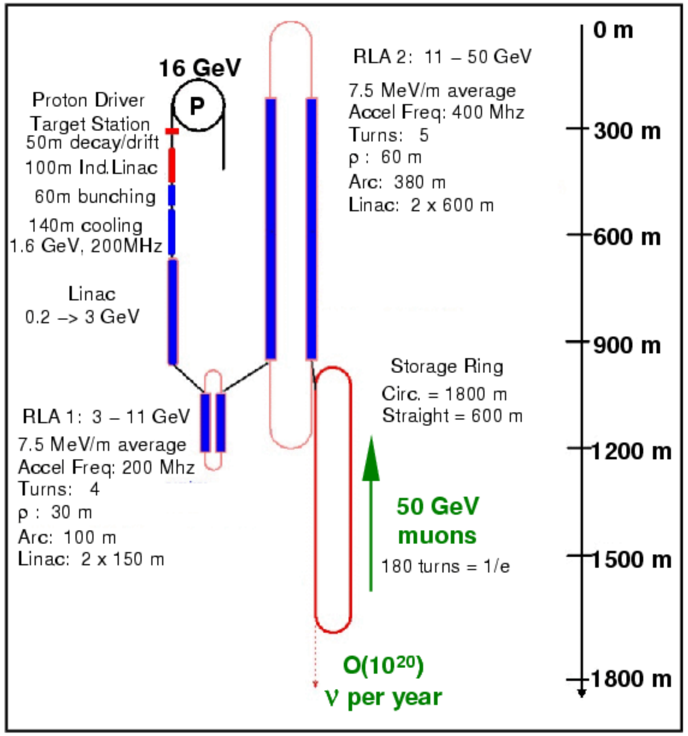


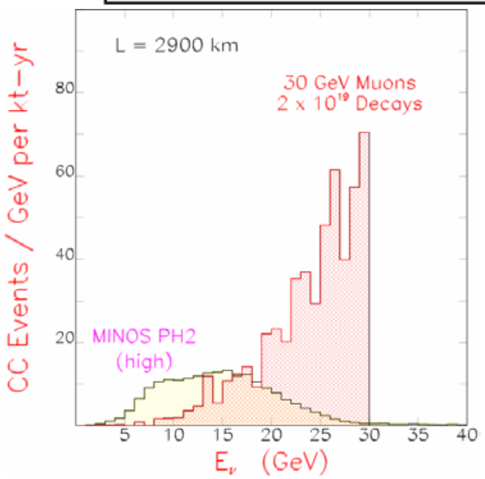



Existing Far detector site

Even more future projects (>20~30yrs?)

Neutrino Factory

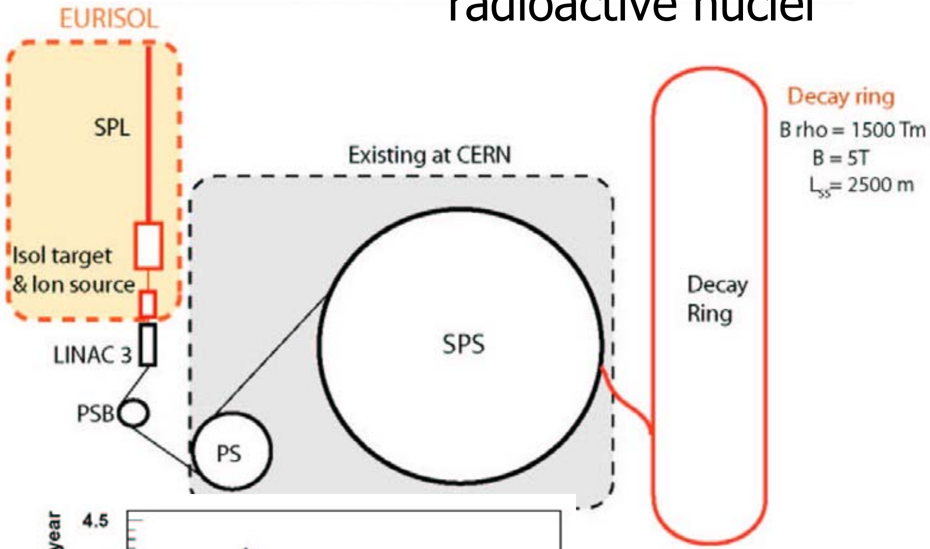


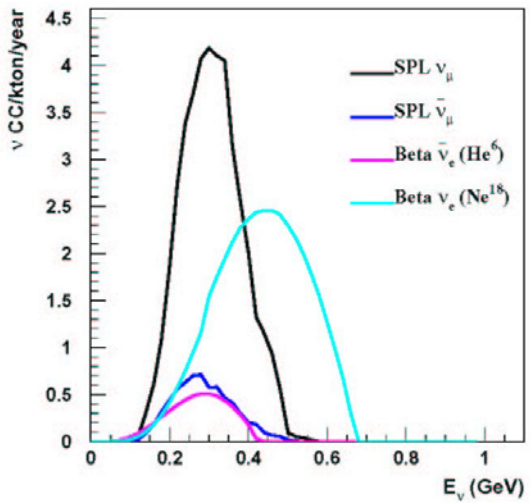


$\nu_\mu/\overline{\nu}_e$ from accelerated muons
- No ambiguity in flux
- High intensity
  $\nu e \rightarrow \nu\mu$
- Need magnetized det.

Beta Beam

ν_e from accelerated radioactive nuclei





Pure ν_e
No ambiguity in flux

Need to establish basic technologies

Summary

- **Neutrino oscillation established**
  - Atm ν/K2K → θ_{23}, Δm_{23}^2
  - Solar/KamLAND → θ_{12}, Δm_{12}^2
- **Next important issues**
  - Discovery and measurement of only unknown mixing θ_{13}
  - Mass hierarchy
  - CP violation
- **Future LBL exp's have good chance to achieve the goals**
  - T2K using J-PARC and SK started construction. Start exp. In 2009
    - θ_{13} sensitivity ~0.007 (90%CL)
    - $|\delta|$~20deg in phase 2
  - NOνA proposal w/ similar potential to T2K
- **Pure θ_{13} measurements by reactor experiments**
  - complementary to disentangle parameter relations
    θ_{13} sensitivity 0.01~0.03 (90%)
  - Systematic error (<1%) is key issue
  - Double-CHOOZ is partially approved
- **Neutrino will continue to be exciting for coming decades**